CSI 2264: CHARACTERIZING YOUNG STARS IN NGC 2264 WITH STOCHastically VARYING LIGHT CURVES*  

JOHN STAUFFER1, ANN MARIE CODY2, LUISA REBUFFI1, LYNNE A. HILLENBRAND3, NEAL J. TURNER4, JOHN CARPENTER3, SEAN CAREY1, SUSAN TEREBEY3, MARÍA MORALES-CALDERÓN6, SILVIA H. P. ALENCAR7, PAULINE MCGINNIS8, ALANA SOUSA7, JEROME BOUVIER8,9, LAURA VENuti8,9, LEE HARTMANN10, NURIA CALVET10, GIUSI MICELA11, ETTORE FLACCIOMO11, INSEOK SONG12, ROB GUTERMUTH13, DAVID BARRADO6, FREDERICK J. VRBA14, KEVIN COVEY15, WILLIAM HERBST16, EDWARD GILLEN17, MARCELO MEDEIROS GUIMARÃES18, HÉRVE BOΥ19, AND FABIO FAVATA19

1 Spitzer Science Center, California Institute of Technology, Pasadena, CA 91125, USA; stauffer@ipac.caltech.edu  
2 NASA Ames Research Center, Kepler Science Office, Mountain View, CA 94035, USA  
3 Astronomy Department, California Institute of Technology, Pasadena, CA 91125, USA  
4 Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA  
5 Department of Physics and Astronomy, 5151 State University Drive, California State University at Los Angeles, Los Angeles, CA 90032, USA  
6 Centro de Astrobiología, Dpto. de Planetología y de Astrofísica de Grenoble (IPAG), F-38000 Grenoble, France  
7 Departamento de Física—CEEx, Av. Antônio Carlos, 6627, 30270-901, Belo Horizonte, MG, Brazil  
8 Université de Grenoble, Institut de Planétologie et d’Astrophysique de Grenoble (IPAG), F-38000 Grenoble, France  
9 CNRS, IPAG, F-38000 Grenoble, France  
10 Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48105, USA  
11 INAF—Osservatorio Astronomico di Palermo, Piazza del Parlamento 1, I-90134, Palermo, Italy  
12 Department of Physics and Astronomy, The University of Georgia, Athens, GA 30602-2451, USA  
13 Department of Astronomy, University of Massachusetts, Amherst, MA 01003, USA  
14 U.S. Naval Observatory, Flagstaff Station, 10391 West Naval Observatory Road, Flagstaff, AZ 86001, USA  
15 Department of Physics and Astronomy (MS-9164), Western Washington Univ., 516 High St., Bellingham, WA 98225, USA  
16 Astronomy Department, Wesleyan University, Middletown, CT 06459, USA  
17 Department of Physics, University of Oxford, Keble Road, Oxford, OX1 3RH, UK  
18 Departamento de Física—UFS—Rod. Marechal Rondon, 49100-000, São Cristóvão, SE, Brazil  
19 European Space Agency, 8-10 rue Mario Nikis, F-75738 Paris Cedex 15, France  

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ABSTRACT

We provide CoRoT and Spitzer light curves and other supporting data for 17 classical T Tauri stars in NGC 2264 whose CoRoT light curves exemplify the “stochastic” light curve class as defined in 2014 by Cody et al. The most probable physical mechanism to explain the optical variability within this light curve class is time-dependent mass accretion onto the stellar photosphere, producing transient hot spots. Where we have appropriate spectral data, we show that the veiling variability in these stars is consistent in both amplitude and timescale with the optical light curve morphology. The veiling variability is also well-correlated with the strength of the He i 6678 Å emission line, predicted by models to arise in accretion shocks on or near the stellar photosphere. Stars with accretion burst light curve morphology also have variable mass accretion. The stochastic and accretion burst light curves can both be explained by a simple model of randomly occurring flux bursts, with the stochastic light curve class having a higher frequency of lower amplitude events. Members of the stochastic light curve class have only moderate mass accretion rates. Their H α profiles usually have blueshifted absorption features, probably originating in a disk wind. The lack of periodic signatures in the light curves suggests that little of the variability is due to long-lived hot spots rotating into or out of our line of sight; instead, the primary driver of the observed photometric variability is likely to be instabilities in the inner disk that lead to variable mass accretion.

Key words: circumstellar matter – open clusters and associations: individual (NGC 2264) – stars: pre-main sequence – stars: protostars – stars: variables: T Tauri, Herbig Ae/Be

1. INTRODUCTION

The published literature on the photometric variability of T Tauri stars now extends back in time more than 150 years (Schmidt 1861, 1866), predating by nearly 100 years the general acceptance that T associations are sites of recent/current star formation (Ambartsumian 1954; Salpeter 1954), and therefore that the photometric variability of T Tauri stars is likely a signpost of youth (Walker 1956). Haro & Herbig (1955) and Walker (1956) discovered that many of the photometrically variable T Tauri stars also had UV excesses and abnormally weak photospheric absorption lines (now usually described as spectral “veiling”); the former authors concluded that the UV excesses might originate from a small hot spot on or near the stellar photosphere. However, it was not until the 1970s that the modern paradigm for young stellar objects (YSOs) began to develop, first by linking the photospheric hotspots to accretion from a disk (Walker 1972; Wolf et al. 1977), and eventually by having the accretion stream be channeled by magnetic field lines connecting the star and inner disk (Ghosh & Lamb 1978; Königl 1991). Based on photometry derived from visual observations or photographic plates, Joy (1945) made photometric variability

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one of the defining characteristics of the T Tauri class of stars. Only the largest amplitude variables could be identified with those techniques. The modern era in the study of the photometric variability of T Tauri stars began in the 1980s in a series of papers by Herbst and his students (Herbst et al. 1982, 1987; Holtzman et al. 1986) and by Vrba and his collaborators (Rydgren & Vrba 1983; Vrba et al. 1986, 1989). They showed that very young stars often have spotted photospheres, allowing their rotation periods to be derived (which showed that many of them are rapidly rotating relative to the Sun, as had long been known from spectroscopy, e.g., Walker 1956). In many cases, the data were compatible with cold spots as found on the Sun; however, in some cases—particularly when photometry over a broad wavelength range was available—the data were best fit by spots hotter than the stellar photosphere, confirming the speculation of Haro & Herbig (1955). Other T Tauri stars instead showed apparently chaotic (or at least aperiodic) variability. Herbst et al. (1994) summarized the existing data on T Tauri variability, and proposed sorting the light curves into several physically motivated classes:

1. Type I—light curves resulting from stable, long-lived cold spots that are not distributed in an axisymmetric way over the stellar photosphere. The resultant light curves are periodic, and persist with little change often for months to years;

2. Type II—light curves dominated by relatively short lived hot spots. Often these do not show obvious periodicity, indicating that the hot spots evolve significantly on timescales less than the stellar rotation period;

3. Type III—hot spot light curves where the spot lifetime is instead comparable to or larger than the stellar rotation period, resulting in more or less periodic variations—but which generally evolve rapidly;

4. Type IV—young stars with large amplitude flux variations in their light curves which are not accompanied by significant variations in the veiling inferred from spectroscopy. The physical interpretation of this class was uncertain, though the leading candidate was extinction by clumps of dust (most plausibly connected to structures in the inner circumstellar disk).

In the past two decades, time series photometry in star-forming regions has been used primarily to determine rotation periods in order to study the initial angular momentum distribution for low mass stars (Herbst et al. 2000; Rebull 2001; Lamm et al. 2005; Moraux et al. 2013). Those programs have been quite successful, with rotation periods now known for more than a thousand low mass stars with ages less than a few Myr. Some programs have continued to attempt to characterize YSO variability not due to spots (e.g., Carpenter et al. 2001), including a series of campaigns aimed at a particularly intriguing YSO—AA Tau (Bouvier et al. 1999; Terquem & Papaloizou 2000; Bouvier et al. 2003). Based on intensive ground-based time series photometry and spectroscopy over several years, the latter set of papers provided evidence that the light curve for AA Tau is dominated by variable extinction caused by a warped inner disk periodically intersecting our line of sight. More recently, using three weeks of continuous, high signal-to-noise ratio (S/N) photometry from the CoRoT satellite, Alencar et al. (2010) showed that many of the classical T Tauri stars (CTTS) in the star-forming region NGC 2264 have light curves similar to AA Tau, indicating that variable extinction from structures in the circumstellar disk passing through our line of sight is common.

This paper is based on a number of observational efforts organized around a Spitzer Space Telescope Exploration Science program entitled “A Coordinated, Synoptic Investigation of Star Formation in NGC 2264” (aka CSI 2264). CSI 2264 combines simultaneous or contemporaneous time series observations of the entire NGC 2264 star-forming region spanning a wide range in wavelength and including both photometry and spectroscopy. Cody et al. (2014) provide an overview of the program and propose a new, quantitative light curve classification scheme for YSOs based on indices that measure the degree of periodicity and the degree of symmetry of the light curves. Stauffer et al. (2014) identified and characterized the members of one of these classes—CTTS whose light curves are dominated by short-duration flux bursts. McGinnis et al. (2015) and Stauffer et al. (2015) similarly identify and characterize CTTS whose light curves are dominated by variable extinction events. L. Venuti et al. (2016, in preparation) discuss all of the NGC 2264 stars whose CoRoT light curves are periodic or quasi-periodic. Figure 1 illustrates stars whose light curves are dominated by variable extinction, accretion bursts, cold or hot spots, and a prototype of the stochastic light curve class, the topic of this paper.

The last remaining, major light curve class identified by Cody et al. (2014) for which our group has not yet published a detailed characterization paper are the stars designated as having stochastic light curves. Light curves in this class show variability with no definite periodicity and also show symmetric shapes (that is, they do not appear to have a continuum level punctuated by dips—as for the variable extinction stars—nor a continuum level punctuated by discrete flux excesses—as for the accretion burst stars). The goal of this paper is to illustrate in more detail the characteristics of the stars with stochastic optical light curves, and to propose a physical mechanism for their variability. In Section 2, we give a brief listing of the observational data obtained as part of the CSI 2264 program. In Section 3, we identify a set of seventeen CTTS whose light curves we consider to exemplify the stochastic class, we provide additional empirical data for these stars, and we compare their properties to other CTTS members of NGC 2264. We believe the most plausible physical mechanism to explain the optical variability of the stars with stochastic light curves to be variable accretion onto the star’s photosphere, and we provide our arguments for that conclusion in Section 4. Additional characterization of the stochastic light curve stars is provided in Section 5. In Section 6, we summarize the properties of the stochastic light curve class members and discuss connections to physical models and how future observations could improve our understanding of these stars.

2. OBSERVATIONAL DATA

A detailed description of the data we collected in our 2008 and 2011 observing campaigns for the NGC 2264 star-forming region is provided in Cody et al. (2014).20 The subset of the data sources that we use here is based primarily on the synoptic

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20 The CoRoT and Spitzer light curves for all probable NGC 2264 members, as well as our broad band photometry for these stars, are available at http://irsa.ipac.caltech.edu/data/SPITZER/CSI2264. As of 2015 June, calibrated versions of all VLT/FLAMES spectra obtained prior to 2014 December—including those taken for both CSI 2264 and ESO-Gaia—are available at http://archive.eso.org/wdb/wdb/adp/phase3_spectral.
Figure 1. Light curves for five CTTS members of NGC 2264 whose CoRoT light curves illustrate morphologies to which we have ascribed physical mechanisms including variable extinction (panels (a) and (b)), unstable accretion or accretion burst (panel (c)), cold spots (panel (d)), and hot spots (panel (e)), and a sixth CTTS that shows a typical stochastic light curve (panel (f)). The variable extinction exemplars include an AA Tau analog (Mon-250) and a star with aperiodic flux dips possibly due to instability events briefly raising dust structures above the quiescent disk photosphere (Mon-676). The Mon-1114 light curve also includes two isolated short-duration flux dips near days 30 and 35 of the type which we associate with extinction due to dust entrained in accretion streams (Stauffer et al. 2015).
Table 1
Synoptic Data Used in This Paper

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Data Type</th>
<th>Wavelength(s)</th>
<th>Resolution</th>
<th>Date Range (MJD)</th>
<th>Cadence</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoRoT</td>
<td>Optical Photometry</td>
<td>6000 Å</td>
<td>2</td>
<td>54534–54556</td>
<td>32 s or 512 s</td>
</tr>
<tr>
<td>CoRoT</td>
<td>Optical Photometry</td>
<td>6000 Å</td>
<td>2</td>
<td>55897–55936</td>
<td>32 s or 512 s</td>
</tr>
<tr>
<td>Spitzer</td>
<td>IR Photometry</td>
<td>3.6 and 4.5 μm</td>
<td>4</td>
<td>55900–55930</td>
<td>2 hr</td>
</tr>
<tr>
<td>USNO 1.0 m</td>
<td>Optical Photometry</td>
<td>7000 Å</td>
<td>8</td>
<td>55890–55990</td>
<td>few dozen per night</td>
</tr>
<tr>
<td>CFHT</td>
<td>Optical Photometry</td>
<td>ugr</td>
<td>10</td>
<td>55971–55986</td>
<td>~3 times per night</td>
</tr>
<tr>
<td>VLT/FLAMES</td>
<td>Spectroscopy</td>
<td>6450–6750 Å</td>
<td>17000</td>
<td>55899–55981</td>
<td>~20 spectra in 90 nights</td>
</tr>
<tr>
<td>VLT/FLAMES</td>
<td>Spectroscopy</td>
<td>6450–6750 Å</td>
<td>17000</td>
<td>56648–56660</td>
<td>~1 spectrum per night</td>
</tr>
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Table 2
Basic Information for YSOs with Stochastic Optical Light Curve Shapes

<table>
<thead>
<tr>
<th>Mon ID(^a)</th>
<th>2MASS ID</th>
<th>CoRoT(^b)</th>
<th>SpT(^c)</th>
<th>Hα EW(^d) (Å)</th>
<th>FR4.5(^e)</th>
<th>CoRoT Ampl.(^e) (mag)</th>
<th>(J_{\text{Stetson}}) (\text{opt-IR})</th>
<th>SED Slope(^f)</th>
<th>(\tau_{\text{opt}}) (\text{h})</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSIMon-000119(^g)</td>
<td>06412100 + 0933361</td>
<td>2323985897</td>
<td>K6 (*)</td>
<td>-10.6</td>
<td>2.9</td>
<td>0.27</td>
<td>2.30</td>
<td>-1.42</td>
<td>1.6</td>
</tr>
<tr>
<td>CSIMon-000242</td>
<td>06411185 + 0926214</td>
<td>602079796</td>
<td>K7 (*)</td>
<td>-5.4</td>
<td>0.4</td>
<td>0.14</td>
<td>1.16</td>
<td>-1.39</td>
<td>5.3</td>
</tr>
<tr>
<td>CSIMon-000546</td>
<td>06410908 + 0930090</td>
<td>603402478</td>
<td>K7 (*)</td>
<td>-27</td>
<td>4.1</td>
<td>0.28</td>
<td>0.78</td>
<td>-0.63</td>
<td>1.5</td>
</tr>
<tr>
<td>CSIMon-000425</td>
<td>06411686 + 0929522</td>
<td>616943882</td>
<td>K5 (*)</td>
<td>-6.3</td>
<td>2.4</td>
<td>0.30</td>
<td>1.31</td>
<td>-1.02</td>
<td>1.1</td>
</tr>
<tr>
<td>CSIMon-000457(^h)</td>
<td>06410673 + 0934459</td>
<td>616919789</td>
<td>G6 (*)</td>
<td>-49.4</td>
<td>&gt;10</td>
<td>0.18</td>
<td>0.97</td>
<td>-0.18</td>
<td>3.7</td>
</tr>
<tr>
<td>CSIMon-000491(^h)</td>
<td>06405616 + 0936309</td>
<td>616895873</td>
<td>K3 (*)</td>
<td>-67.2</td>
<td>5.2</td>
<td>0.50</td>
<td>0.41</td>
<td>-0.63</td>
<td>4.6</td>
</tr>
<tr>
<td>CSIMon-000577</td>
<td>06413482 + 0940500</td>
<td>616895846</td>
<td>K1 (*)</td>
<td>-5.9</td>
<td>2.9</td>
<td>0.10</td>
<td>0.72</td>
<td>-1.55</td>
<td>1.3</td>
</tr>
<tr>
<td>CSIMon-000613(^h)</td>
<td>06410577 + 0948174</td>
<td>616849463</td>
<td>K6.5 (*)</td>
<td>-30.1</td>
<td>2.1</td>
<td>0.14</td>
<td>0.92</td>
<td>-1.51</td>
<td>1.4</td>
</tr>
<tr>
<td>CSIMon-000636(^h)</td>
<td>06404884 + 0943256</td>
<td>616872578</td>
<td>M0 (*)</td>
<td>-15.5</td>
<td>5.4</td>
<td>0.49</td>
<td>1.63</td>
<td>-0.57</td>
<td>1.2</td>
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<tr>
<td>CSIMon-000795(^h)</td>
<td>06411257 + 0952311</td>
<td>500007115</td>
<td>GV6 (*)</td>
<td>-35.3</td>
<td>2.5</td>
<td>0.22</td>
<td>...</td>
<td>-1.55</td>
<td>0.5</td>
</tr>
<tr>
<td>CSIMon-000985</td>
<td>06401515 + 1001578</td>
<td>223396998</td>
<td>G8 (*)</td>
<td>-91</td>
<td>&gt;10</td>
<td>0.51</td>
<td>1.99</td>
<td>-1.12</td>
<td>0.7</td>
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<tr>
<td>CSIMon-001054(^h)</td>
<td>06403652 + 0950456</td>
<td>400007538</td>
<td>M2 (*)</td>
<td>-21.1</td>
<td>2.0</td>
<td>0.15</td>
<td>0.53</td>
<td>-1.29</td>
<td>0.8</td>
</tr>
<tr>
<td>CSIMon-001061</td>
<td>06402416 + 0934124</td>
<td>616919835</td>
<td>M5 (*)</td>
<td>-33.0</td>
<td>3.5</td>
<td>0.33</td>
<td>1.99</td>
<td>-1.06</td>
<td>0.8</td>
</tr>
<tr>
<td>CSIMon-001234(^h)</td>
<td>06401113 + 0938059</td>
<td>223368039</td>
<td>K6 (*)</td>
<td>-52.9</td>
<td>1.4</td>
<td>0.60</td>
<td>1.55</td>
<td>-1.39</td>
<td>0.8</td>
</tr>
<tr>
<td>CSIMon-001267</td>
<td>06403431 + 0925171</td>
<td>616940066</td>
<td>G5 (*)</td>
<td>-15.0</td>
<td>5.4</td>
<td>0.25</td>
<td>...</td>
<td>-0.47</td>
<td>1.1</td>
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<tr>
<td>CSIMon-006491</td>
<td>06392550 + 0931394</td>
<td>616920065</td>
<td>K4 (*)</td>
<td>-6.2</td>
<td>1.7</td>
<td>0.29</td>
<td>1.64</td>
<td>-1.52</td>
<td>0.5</td>
</tr>
<tr>
<td>CSIMon-006930</td>
<td>06390409 + 0916139</td>
<td>223948224</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>0.18</td>
<td>...</td>
<td>...</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Notes.
\(^a\) The CSIMon IDs are our internal naming scheme for stars in the field of NGC 2264—see Cody et al. (2014) and http://irsa.ipac.caltech.edu/data/SPITZER/CS2264. In the main text of this paper, we omit the “CSI” and the leading zeros in the object names for brevity. \(^b\) = synoptic VLT spectra from 2011 available; \(^c\) CoRoT identification number. Three stars were observed in both 2008 and 2011, but had different ID numbers in 2008—the 2008 CoRoT ID number for those three stars are 500007221 (Mon-242), 500007369 (Mon-457), and 500007548 (Mon-1267). \(^d\) Spectral types marked with an asterisk have their types estimated from the dereddened CFHT photometry and the Pecaut & Mamajek (2013) young star relation between effective temperature and spectral type; see Venuti et al. (2014). The Hα equivalent widths for these stars come from our spectra. All the other spectral types and Hα equivalent widths are from Dahn & Simon (2005), except for Mon-636 where the spectral type is from Makidon et al. (2004). \(^e\) FR4.5 is an estimate of the ratio of the flux from the disk to the flux from the stellar photosphere at 4.5 μm, based on all the available broad-band photometry and the published spectral types. Because the SED models do not include veiling, these values are likely lower limits. \(^f\) The 10%–90% amplitude of the CoRoT light curves. When we have data for both 2008 and 2011, the CoRoT amplitude corresponds to the epoch plotted in Figure 2 and Figure 3. \(^g\) Stetson index between the CoRoT 2011 light curve and the IRAC [4.5] light curve. A colon following the value indicates we only have a small number of IRAC photometry points, making the value uncertain. \(^h\) Spectral energy distribution (SED) slope from 2 to 8 μm, derived as in Rebull et al. (2014). \(^i\) Optical light curve timescale, as discussed in Section 5.4.

Data we obtained with CoRoT, Spitzer, VLT/FLAMES, Canada–France–Hawaii Telescope (CFHT) and the USNO 1.0 m telescopes, which we summarize in Table 1.

In addition to the synoptic data, we also use several single epoch data sources in order to help characterize the overall properties of the NGC 2264 members. These data sets include:

1. Single epoch ugr imaging of the entire cluster, with standard Sloan Digital Sky Survey filters, obtained using Megacam on the CFHT during two observing runs in 2010 and 2012. These data are presented in detail in Venuti et al. (2014). We also make use of single-epoch UBVR data from Sung et al. (2008).
2. Spitzer IRAC 3.6, 4.5, 5.8 and 8.0 μm and MIPS 24 μm single epoch imaging photometry of the entire cluster obtained early in the cryogenic mission, and reported in Sung et al. (2009) and Teixeira et al. (2012).
3. Single epoch FLAMES spectra for many of the NGC 2264 members, originally obtained as part of the ESO-Gaia program (Randich et al. 2013). We downloaded the raw spectra from the ESO-Gaia archive for these stars, and produced our own calibrated spectra.
We have used the VLT/FLAMES spectra to analyse Hα profiles, spectral veiling, projected rotational velocities and emission line FWHM as diagnostics of accretion and the geometry of the CTTS disks. Details of this analysis are generally discussed in the Appendix.

3. THE YSOs IN NGC 2264 WITH STOCHASTIC LIGHT CURVES

As noted in Section 1 and in Cody et al. (2014), the stochastic light curve class includes stars whose CoRoT photometry shows little or no periodic signature and for which the light curve has no significant preference for upward excursions or downward excursions (they appear symmetric when reflected about their median level). Quantitatively, this corresponds to \( Q > 0.61 \) and \(-0.25 < M < 0.25\) using the Cody et al. (2014) metrics, where the \( Q \) metric is a measure of the light curve periodicity (or stochasticity) and the \( M \) metric quantifies the degree of symmetry of the light curve relative to its median level. Light curves for prototypes of the stochastic class are shown in Figure 18 of Cody et al. (2014). Those light curves resemble model light curves produced by damped random walk processes (Findeisen et al. 2015), which is the reason for adopting “stochastic” as the descriptive name for this class.

Because Cody et al. (2014) considered only the 2011 CoRoT data (and not the 2008 campaign) and because our membership list has evolved slightly since that paper was written, we have conducted a thorough review of all of our data in order to construct the list of stochastic stars to analyse in this paper. We also have chosen to add two additional criteria in order to make the sample more characterizeable and more “pure.” First, we require that the full amplitude of the CoRoT light curve be greater than 0.1 mag; this criterion makes it more likely that we will be able to detect correlations between the CoRoT light curve shape and other data. Second, we have attempted to exclude stars whose light curve morphology appears to be better described as a mix of similar amplitude accretion bursts and extinction dips. Light curves with features arising from a mixture of mechanisms is both possible and expected; however, we have associated specific physical mechanisms already with accretion burst signatures and extinction dips. Separating truly random walk light curve morphologies from this kind of mixed mechanism morphology is admittedly subjective, and we probably have not been completely successful. However, because our goal is not to identify a complete set of objects but is instead to identify the physical mechanism driving this light curve morphology, we believe this process is acceptable.

Table 2 presents the list of NGC 2264 YSOs whose light curve satisfy our criteria. The table provides our internal name for the star, as well as the 2MASS and CoRoT designations. In addition, we provide spectral type, Hα equivalent width, light curve amplitude in the optical and infrared, an optical–IR Stetson index (Stetson 1996), a spectral energy distribution (SED) slope, and a timescale (see Section 5.4). The suite of single-epoch broadband photometry we have for each of these stars is provided in Table 3; most of these data have appeared previously in Venuti et al. (2014) and Cody et al. (2014)—we repeat their values here in order to allow readers to easily associate specific stars to specific points in the color–color and color–magnitude plots we show. The CoRoT light curves for each of these stochastic light curve stars are provided in Figures 2 and 3. There are of order 175 CTTS with good CoRoT light curves; with seventeen stars in the stochastic light curve class, the frequency of occurrence for light curves of this type and our selection criteria is of order 10% (versus 13% in Cody et al. 2014 using their slightly different selection criteria and their slightly different membership list).
Though we have not required the stars in Table 2 to have $Q$, $M$ metrics that satisfy the Cody et al. (2014) criteria, most of them do so, as is illustrated in Figure 4. Our sample includes two stars whose light curve metrics fall slightly outside the nominal stochastic-class $QM$ box boundary. One of them (Mon-457) has CoRoT light curves in both 2008 and 2011; the 2008 light curve falls within the $QM$ box, whereas the 2011 light curve falls slightly below the $QM$ lower boundary. The other star whose light curve is slightly below the lower $QM$ boundary is Mon-242; we include it in Table 2 simply because its light curve morphology seems best matched to this class.

Seven additional stars also satisfy the $QM$ criteria for having stochastic light curves, but we believe they are better classified as belonging to other groups. The light curves for these seven stars are shown in the Appendix in Figure 20. The stars in Figure 20 include three stars (Mon-11, Mon-510 and Mon-996) which we classified as having accretion-burst dominated light curves and included in Stauffer et al. (2014); two additional accretion burst dominated stars (Mon-766 and Mon-1048), one star which we believe is best interpreted as having a light curve dominated by a combination of accretion bursts and flux dips due to variable extinction (Mon-1294), and one star (Mon-774) whose 2011 light curve we attribute to aperiodic extinction dips. Other interpretations could be made for the 2011 Mon-774 light curve; our choice was strongly influenced by the fact that its 2008 light curve was clearly that of an AA Tau analog (periodic, deep, broad flux dips due to variable extinction) and that stars with AA Tau-type light curves often switch to aperiodic flux dip dominated light curves at other epochs (McGinnis et al. 2015).

While the $Q$ and $M$ statistics for the stars in Figure 2 and Figure 3 assign them to the same morphological light curve class, at first glance their light curves nevertheless appear somewhat heterogeneous. In significant part, that is because the characteristic timescales for their variations differ (see Section 5). Specifically, some of the stars have quite short characteristic timescales (e.g., Mon-346, 577, 985 and 6491), whereas others have relatively long timescales (e.g., Mon-425, 457, 491). In order to better illustrate the similarity of their light curves, Figure 5 shows the light curves of two of the stars with short timescales in an expanded view. With the $x$-axis expanded roughly five times in scale, the light curves for these two stars (Mon-346 and Mon-985) look much more similar to the light curves for the long timescale members of the class.

Before proceeding to our discussion of the CoRoT light curves for the stochastic stars and the probable physical mechanism causing their optical variability, it is useful to consider the physical properties of these stars as derived from...
their mean observed colors and spectral types. If these stars differ in some significant aspect from the other CTTS in NGC 2264, that could help us interpret their photometric variability. Toward this end, we provide four diagnostic plots: a \(g\) versus \((g - i)\) color–magnitude diagram (CMD); a \((u - g)\) versus \((g - r)\) color–color plot; a \((J - H)\) versus \((H - K_s)\) near-IR color–color plot, and the IRAC \([3.6] - [4.5]\) versus \([5.8] - [8.0]\) color–color plot. Our conclusions from these plots and the data listed in Tables 2 and 3 are:

1. From the near-IR color–color diagram (Figure 6(a)), we infer that on average the stochastic stars have relatively small extinctions, comparable to, but probably on average somewhat larger than those for the accretion burst and variable extinction classes (a list of the accretion burst and variable extinction stars plotted in these four figures and used elsewhere in the paper is provided in Table 5). This agrees with extinction estimates derived from combining the observed \((V - I)\) colors (Sung et al. 2008), published spectral types (Table 2 and Cody et al. 2014), and standard colors for young stars from Pecaut & Mamajek (2013), where the median \(E(V - I)\) colors are 0.42, 0.05 and 0.15 for the stochastic, accretion burst and variable-extinction classes, respectively. The derived \(E(V - I)\) for the accretion burst stars is probably an underestimate because their \((V - I)\) colors are significantly influenced by hot spots, while the \(E(V - I)\) colors of the variable extinction stars may be underestimated if scattered light from the disk contributes significantly to their optical flux. The three stochastic stars with the largest \((H - K_s)\) colors (Mon-457, 491, and 985) also have the largest disk to photosphere contrast ratios at 4.5 \(\mu m\) (see Table 2, column 7), demonstrating that their light is disk-dominated in the IR.

2. From the optical CMD (Figure 6(b)), we conclude that the stochastic stars are not, on average, displaced “vertically” relative to the other CTTS groups nor relative to the weak-lined T Tauri (WTTS) sample. If the CMD can be used to infer relative ages, this indicates no significant age difference between these stars despite their quite different light curve morphologies. As shown in Table 2, the stochastic class includes YSOs with spectral types spanning the entire \(G\) to mid-\(M\) range. The stochastic and variable extinction classes dominate the upper-left portion of the CMD, indicating they probably include a larger fraction of high mass CTTS compared to the accretion burst class. Comparison of the spectral type

\[\text{Figure 3. CoRoT light curves for the other seven NGC 2264 CTTS which we consider as having stochastic light curves.}\]
1. but become bluer in
stable, cold spots
inside the cyan box
and the location of the stars studied in this paper within that plot
illustrating the quantitative light curve morphology classi
classify as having stochastic light curves
variable extinction light curve; and green circles and triangles are stars we
Plot derived from the
Figure 4.

![Figure 4](image)

**Figure 4.** Plot derived from the CoRoT light curves for CTTS in NGC 2264
illustrating the quantitative light curve morphology classification technique, and
the location of the stars studied in this paper within that plot (the region
inside the cyan box). \( Q < 0.11 \) corresponds to periodic light curves (typically
reflective of rotational modulation of a stellar photosphere mottled by relatively
stable, cold spots); \( 0.11 < Q < 0.61 \) indicates quasi-periodicity (Cody
et al. 2014), typically corresponding to light curves showing periodic structure
whose waveform evolves significantly from period to period as often true for
AA Tau-analogs; and \( Q > 0.61 \) indicates stars with little or no periodic
signature. Blue triangles denote stars with accretion burst light curves located
within the stochastic region (cyan box); blue stars have light curves with both
accretion bursts and narrow flux dips; the red triangle marks a star with a
variable extinction light curve; and green circles and triangles are stars we
classify as having stochastic light curves (with the triangles being those with
only limits on \( Q \)).

distributions for the three classes confirms this difference
(see Section 5.2).

(3) Figure 7(a), the \((u - g)\) versus \((g - r)\) diagram, has been
used as an accretion diagnostic in Venuti et al. (2014).
Young stars without on-going accretion form an inverted
V in this diagram, with early G stars located near
\( g - r = 0.5, \ u - g = 2.0 \), and with both colors becoming
redder to later spectral types until about M0 (at
\( g - r \sim 1.4, \ u - g \sim 2.8 \)). Later M spectral types retain
\( g - r \sim 1.4 \) but become bluer in \( u - g \), presumably due
to enhanced chromospheric emission. Reddening shifts
stars toward the upper right in the diagram; accretion
primarily shifts stars down but also slightly to the left.
The diagram shows that, on average, the stochastic stars
have smaller UV excesses than the stars with accretion-burst
dominated light curves, but comparable UV
excesses as for the variable extinction sample. A
Student-T test yields a less than \( 10^{-4} \) probability that
the accretion burst stars are drawn from the same parent
population as the other two classes, but finds no
significant difference between the stochastic and variable
extinction classes. Also in support of these conclusions,
the median H\( \alpha \) equivalent widths for the stochastic,
accretion burst and variable extinction classes are \(-18, -68, \) and \(-16 \AA \), respectively.

(4) Figure 7(b) shows the IRAC two-color diagram for the
same set of stars. All of the stochastic stars fall within the
Class II box defined in Allen et al. (2004) or slightly
redward of that box. This suggests that their inner disks
are similarly dusty, on average, as the accretion-burst
dominated class (which have a very similar distribution of
points in this diagram). The stochastic stars have redder
IRAC colors, on average, compared to the stars in the
variable extinction light curve class (a Student-T test
yields a 1% probability that the two classes have the same
parent population colors for each axis). Comparison of
the mean SED slopes from 2 to 8 \( \mu \)m yields a similar
result, with mean slopes of \(-1.08, -1.21, \) and \(-1.54
(and statistical uncertainties of about 0.10 for each of
these values) for the stochastic, accretion burst and
variable extinction classes, respectively.

4. VARIABLE ACCRETION AS THE PHYSICAL
MECHANISM TO EXPLAIN THE STOCHASTIC LIGHT
CURVES

In the Herbst et al. (1994) taxonomy, stars in their Type II
light curve category would generally map into Cody’s
stochastic class. Herbst et al. advocated that the most probable
physical mechanism to explain their Type II light curves was
variable hot spots possibly accompanied by rotational modula-
tion bringing those hot spots into or out of the visible
hemisphere. We agree with that assessment. As noted by
Herbst et al., if this is the case, the light curve modulation
should be accompanied by changes in spectral veiling, resulting in photospheric absorption lines having smaller equivalent widths when the hot spot contribution to the optical light is greater. For the stochastic stars for which we have synoptic VLT spectroscopy, we will show that they do exhibit variable veiling consistent with the amplitude of the optical variability shown in the CoRoT light curves.

The linkage of changes in the spectral veiling to the optical light curve morphology is made difficult because most of our spectroscopy was obtained after the CoRoT photometric campaigns. Also, in some cases, the only photospheric absorption line we can measure accurately is the lithium 6708 doublet, whose equivalent width could be affected by other processes (Basri et al. 1991; Barrado et al. 2001; Baraffe & Chabrier 2010). Our analysis therefore proceeds as follows: (a) for the brighter stars with synoptic VLT spectra, we show that their spectra do show significant veiling variability as measured by several atomic absorption features, and the variability shown by the lithium doublet is well-correlated with the variations in the other absorption features. Figure 8 shows the equivalent width data for these four stars, along with similar data for two of the accretion burst stars. The veiling variability is a natural consequence of a varying hot spot contribution to the star’s continuum flux and is not expected for any of the other mechanisms that are known to drive significant photometric variability in low mass YSOs (e.g., cold spots or variable extinction).

4.1. Veiling and Accretion Variability

For four of the stars with stochastic light curves, we have synoptic VLT spectra of good enough quality to accurately measure equivalent widths for Li I 6708 and at least one other photospheric absorption line. These observations show that there are large variations in the absorption line equivalent widths (veiling variability) over the time period of the VLT campaigns and that the lithium strength variations track well the variations in the other absorption features. Figure 8 shows the equivalent width data for these four stars, along with similar data for two of the accretion burst stars. The veiling variability is a natural consequence of a varying hot spot contribution to the star’s continuum flux and is not expected for any of the other mechanisms that are known to drive significant photometric variability in low mass YSOs (e.g., cold spots or variable extinction).

For the four stars above, plus one additional stochastic star, we have synoptic VLT spectra from which we can accurately measure the Li I 6708 equivalent width and for which the He I 6678 line is sometimes in emission. The He I 6678 line is present in high-resolution spectra for many CTTS, sometimes as a broad feature possibly associated with a hot wind (Beristain et al. 2001), and sometimes as a narrow (FWHM...
variable extinction class. In Figure 7, a $u - g$ vs. $g - r$ color–color diagram for stars with stochastic CoRoT light curves, comparing those stars to CTTS whose light curves we ascribe to variable extinction and to stars whose light curves show short-duration accretion bursts. Small black dots are WTTS; small cyan plus signs are CTTS that are not members of the three light curve classes highlighted in the plot. The diagonal red line is a rough boundary between stars with weak and strong UV excesses (Venuti et al. 2014). Note that one of the stochastic stars—Mon-1267—falls outside the limits of the plot at $g - r = 2.06, u - g = 2.94$. The locus of points for the stochastic light curve stars in this diagram is similar to that for the variable extinction stars (and has much lower UV excesses on average than the accretion burst stars); and (b) mid-IR color–color diagram for the same set of stars. The rectangular box encloses the region dominated by Class II sources as defined in Allen et al. (2004). In this diagram, the stochastic light curve stars have IR colors similar to those for the accretion burst stars, and distinctly redder, on average, compared to the stars in the variable extinction class. From 2013. Even for those stars where we have 2011 multi-epoch spectroscopy, the overlap in time with the CoRoT campaign is small, and we therefore cannot make a useful direct comparison. However, we can make a statistical test—is the inferred range in accretion flux at 6700 Å derived from the veiling data (mostly from 2013) consistent with the measured amplitude in the CoRoT light curves (mostly from 2011)? Figure 10 shows this comparison for the stochastic stars for which we have multi-epoch VLT data. There is considerable scatter in the plot, but the data are consistent with the variable continuum inferred from the spectroscopy matching the variable continuum measured in the light curves—supporting the conclusion that variable accretion is the dominant cause of the optical variability. Finally, having argued that the lithium equivalent widths for CTTS can be used as a relative veiling (and hence accretion) indicator, we can also use the mean lithium equivalent widths for the stochastic light curve stars to estimate their mean veiling levels. In Table 4, we provide mean lithium equivalent widths for the stochastic light curve stars, either measured from our multi-epoch VLT/FLAMES data, or in six cases, as measured from single-epoch VLT/FLAMES spectra obtained by the ESO-Gaia project (Randich et al. 2013). We also provide an estimated maximum photospheric lithium equivalent width for that spectral type,
based on a fit to the upper-envelope of the lithium equivalent widths for all YSOs in NGC 2264 for which we have FLAMES spectra. This allows us to derive an upper limit to the veiling at 6700 Å for each of these stochastic stars. It can be seen that the mean lithium equivalent widths for the stochastic stars differ only slightly from their expected photospheric values, suggesting veilings of generally 10% or less. The median lithium veiling from Table 4 for the stochastic stars is 0.17; for reference, the median veiling for the accretion burst and variable extinction classes are 0.36 and 0.17. The average veiling we derive for the stochastic stars therefore agrees with the conclusion drawn from their UV excesses (Figure 7(a)) that stars of this light curve class have low to moderate accretion rates (significantly lower than stars...
with accretion burst dominated light curves, but similar to the average accretion rate for stars with variable extinction dominated light curves.

4.2. Variable Accretion Inferred from Broadband Colors

If the primary cause of the photometric variability of the stars in Table 2 is variable accretion onto the stellar photosphere, it should also be reflected in the broad-band photometric colors. When the accretion rate is high, the contribution to the optical flux from hot spots should be greatest, and the star should be both brighter and bluer. When the accretion rate is lowest, the hot spots should be at their weakest, and the star should be both fainter and redder.

As noted in Table 1, we have multi-epoch CFHT ugriz photometry for NGC 2264 obtained about a month after the 2011 CoRoT/Spitzer campaign. Venuti et al. (2015) have described these data and used the data to quantify the level of accretion variability for the CTTS in NGC 2264. We now use the same photometry here to test whether accretion variability is the primary driver of the light curve morphology we have ascribed to the stochastic variables in the CoRoT data. As done by Venuti et al. (2015), for each CTTS, we have plotted the change in $r$ magnitude versus the change in $u-r$ color; where those data are well-correlated we have fit a straight-line to the distribution and derived the slope $(\Delta r/\Delta(u-r))$. Figure 11 shows a plot of these slopes for CTTS whose light curve morphologies we have ascribed to short-duration accretion bursts, to cold spots, and to our stars with stochastic light curves. The figure shows that the stochastic light curve stars have color slopes and amplitudes reasonably well-matched to the short-duration accretion burst stars, and qualitatively different from stars whose light curves are dominated by cold spots. Stars whose light curves are dominated by variable extinction can have similar color slopes and amplitudes to those for the stochastic stars (Venuti et al. 2015), but the light curve morphologies of the two classes are quite different.
Table 4
Other Quantitative Data Used in This Paper

<table>
<thead>
<tr>
<th>Mon-ID</th>
<th>(EqWL)L\textsuperscript{a}</th>
<th>Max-EqWL-L\textsuperscript{b} (Å)</th>
<th>(Q)</th>
<th>(M)</th>
<th>(v \sin i) (^d) (km s(^{-1}))</th>
<th>(v \sin i) (^d) (km s(^{-1}))</th>
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<tr>
<td>CSIMon-000119</td>
<td>0.48</td>
<td>0.52</td>
<td>0.62</td>
<td>0.05</td>
<td>21.0</td>
<td>24.8</td>
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<td>CSIMon-000242</td>
<td>0.59\textsuperscript{c}</td>
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<td>0.32</td>
<td>14.9</td>
<td>18.5</td>
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<td>CSIMon-000346</td>
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<td>(\geq 1)</td>
<td>0.14</td>
<td>16.9</td>
<td>16.5</td>
</tr>
<tr>
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<td>(\geq 1)</td>
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<td>42.0</td>
<td>48.4</td>
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<td>0.46</td>
<td>0.99</td>
<td>-0.12</td>
<td>72.0</td>
<td>67.9</td>
</tr>
<tr>
<td>CSIMon-000577</td>
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<td>0.42</td>
<td>0.70</td>
<td>0.09</td>
<td>35.0</td>
<td>34.5</td>
</tr>
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<td>0.64</td>
<td>-0.06</td>
<td>22.0</td>
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<td>0.65</td>
<td>0.04</td>
<td>25.0</td>
<td>24.9</td>
</tr>
<tr>
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<td>0.65</td>
<td>0.06</td>
<td>28.0</td>
<td>35.0</td>
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<tr>
<td>CSIMon-000985</td>
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<td>...</td>
<td>...</td>
<td>0.63</td>
<td>0.08</td>
<td>...</td>
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</tr>
</tbody>
</table>

Notes.
\(\textsuperscript{a}\) Lithium equivalent width averaged over all epochs for the stars for which we have multi-epoch VLT spectra. Where we do not have our own spectra, the value is from measurement of the ESO-Gaia spectrum for this star, and these values are marked with an asterisk.
\(\textsuperscript{b}\) Inferred photospheric lithium equivalent width for a YSO of this star’s spectral type from a fit to the upper envelope of a plot of lithium equivalent width versus spectral type for our NGC 2264 stars for which we have VLT spectra.
\(\textsuperscript{c}\) \(v \sin i\) determined by comparing synthesized, rotationally spun-up model spectra to VLT/FLAMES observed spectra, as described in McGinnis et al. (2015).
\(\textsuperscript{d}\) \(v \sin i\) determined by measuring the FWHM for the LiI 6708 Å doublet and converting that to a \(v \sin i\) using a calibration curve derived from the McGinnis et al. values. Where we have multi-epoch spectra, we measured FWHM for all the spectra and took the mean FWHM as the input.

5. ADDITIONAL CHARACTERIZATION OF THE STOCHASTIC LIGHT CURVE CLASS

5.1. \(H_\alpha\) Profiles of Members of the Stochastic Class

The shapes of emission line profiles for CTTS at least potentially provide clues to their accretion process (Lima et al. 2010; Kurosawa & Romanova 2013). In Stauffer et al. (2014), we showed that NGC 2264 CTTS with accretion-burst light curves had \(H_\alpha\) profiles that were distinctly different, on average, from those for the variable extinction light curve class. Specifically, the \(H_\alpha\) profiles of the accretion burst stars are much more often centrally peaked and lacking in distinct absorption features compared to the variable extinction stars, while the variable extinction stars much more frequently show \(H_\alpha\) absorption dips on the red side of the emission profile. These characteristics are explicable within the theoretical models (Kurosawa & Romanova 2013), with the centrally peaked profiles being a prediction for stars with the highest accretion rates and the redward displaced absorption dips being a consequence of our line of sight intersecting warm gas that is accreting onto the stellar photosphere.

We have good multi-epoch VLT spectra with well-defined \(H_\alpha\) profiles for eight of the stars in Table 2; for another five stars, we have good single epoch \(H_\alpha\) profiles.

Figure 24, in the Appendix, shows typical \(H_\alpha\) profiles for twelve of these stars (the \(H_\alpha\) profile of Mon-613 is not shown in Figure 24, its \(H_\alpha\) profiles are instead shown in Figure 12). \(H_\alpha\) profiles for stars with accretion-burst dominated light curves and for stars whose light curves are dominated by variable extinction events can be found in Figures 6 and 26 of Stauffer et al. (2014).
decreased by about 50%. The velocity offset of the blueshifted absorption dip was essentially constant (at about $-50 \, \text{km s}^{-1}$) for the entire two week interval. The H$\alpha$ profiles of Mon-613 show greater variability, particularly in the height of the blue peak (which varies by more than a factor of two) and the velocity offset of the blue-absorption dip (which was generally about $-60 \, \text{km s}^{-1}$, but was $-100 \, \text{km s}^{-1}$ in the first spectrum). The last two spectra of Mon-613 show two blue-shifted absorption dips, one with $\Delta v = -165 \, \text{km s}^{-1}$ and the other with $\Delta v \sim -50 \, \text{km s}^{-1}$.

Similar but independent models of the H$\alpha$ profiles for CTTS combining both magnetospheric accretion and disk winds have been created by Kurosawa et al. (2006) and Lima et al. (2010). Blue-shifted absorption dips of the type shown in Figures 12 and 24 are predicted to be present in the H$\alpha$ profiles of CTTS primarily having moderately high mass accretion rates and generally having intermediate to low inclination angles ($i \lesssim 55^\circ$). Such blue-shifted absorption dips are believed to arise from gas in a disk wind. If this is indeed the case, the fact that (when we have appropriate spectra) the blue absorption dips are fairly stable on timescales of two weeks or more indicates that the disk wind structure is also relatively stable on those timescales (longer than, for example, the expected photospheric rotation periods of these stars). A more detailed discussion of the H$\alpha$ profiles of all the CTTS for which we have FLAMES data can be found in Sousa et al. (2015).

5.2. Spectral Type and Light Curve Class

It is reasonable to believe that light curve morphology could depend on the mass of the YSO. Higher mass YSOs are likely to have larger mean rotational velocities based on the Kraft “law” ($J/M \propto M^{5/2}$; Kraft 1970) and hence perhaps might have shorter variability timescales. Higher mass YSOs are believed to often have more complex and more non-axisymmetric magnetic fields, while lower mass ($\text{mass} \, >0.5 \, M_{\odot}$) YSOs are expected to have more axisymmetric magnetic fields with strong dipolar components (Gregory et al. 2012). These characteristics are likely to affect the interaction between the star and its circumstellar disk and the resulting accretion patterns.

We do not have any direct mass indicator for the NGC 2264 members, but spectral type should provide a reasonable proxy for mass. Spectral type estimates are available for most of the NGC 2264 CTTS either from the published literature or our own spectra, or estimates of spectral types derived from multi-band photometry (Venuti et al. 2014). Figure 13 compares the spectral type distributions for four sets of CTTS in NGC 2264: (a) the stochastic light curve class; (b) stars with AA Tau-type light curves or with strong, aperiodic flux dips due to variable extinction (McGinnis et al. 2015); (c) stars with accretion burst dominated light curves (Stauffer et al. 2014); and (d) stars with short-duration, nearly Gaussian-shaped flux dips (possibly due to dust entrained in accretion columns; Stauffer et al. 2015). Table 5, in the Appendix, provides the list of stars we have assigned to each group and our adopted spectral types.

The stars in all four light curve classes have a fairly wide range of spectral types. However, there are significant differences in the spectral type distributions, with the stochastic class having the highest fraction of early spectral type stars (four of 15 stochastic stars with estimated spectral types are spectral type $G$, versus only two of sixty for the other three classes combined), while the short-duration flux dip class has a
larger fraction of M dwarfs. Simply assigning numerical equivalents to the spectral types (G5 = 45; K7 = 57; M2 = 62) and then taking averages, the mean spectral types for the four groups are K3 (stochastic), K5 (AA Tau), K7 (burst) and M0 (short-duration flux dip).

5.3. Inferences on the Inclination of the Rotation Axis relative to our Line of Sight

Knowledge of, or at least constraints on, the inclination of a young star’s rotation axis to our line of sight can be very helpful in attempting to determine a physical mechanism to explain the observed variability. For the variable extinction light curve class, if one assumes that the extinction events occur when structures in the inner disk pass through our line of sight, then the presence of the flux dips plus a theoretically modeled disk scale height constrain the inclination of the disk to be $\gtrsim 60^\circ$. Following the simple but physically well-justified CTTS disk model described in Bertout (2000), we assume that on average, there is some inclination angle $i_{\text{min}}$ greater than which the star is always obscured, there is a range of inclinations between $i_{\text{min}}$ and $i_{\text{max}}$ where variable extinction events may occur, and for inclinations less than $i_{\text{min}}$, no disk-related extinction events occur. From the census of CTTS light curves in NGC 2264 (Alencar et al. 2010; McGinnis et al. 2015; Stauffer et al. 2015) we set the fraction of optically visible CTTS with variable extinction events at 25%. Because the estimated line of sight inclination to the disk for the prototype CTTS AA Tau is $i = 70^\circ$–75$^\circ$ (Bouvier et al. 2013), we adopt $i_{\text{min}} = 75^\circ$. With those two parameters set, the Bertout (2000) model then yields $i_{\text{max}} \approx 60^\circ$.

Figure 12. (a) Hα profiles for all twelve epochs obtained during the 2013 VLT/FLAMES campaign for Mon-457. The continuum has been normalized to 1.0 in all spectra, and the y-axis maximum scale has been adjusted so that the peak normalized flux at each epoch approximately coincides. The dot colors correspond to the observing epochs—the spectra from days 1, 4 and 7 are colored blue, spectra from days 8 and 9 are shown in green, day 10 in black, and day 13 in magenta. (b) Same, except for Mon-613.
from that either be able to draw inferences about their inclinations or their intrinsic rotational velocities\textsuperscript{22}. Even that exercise is limited due to the spectral types of the stochastic stars (Figure 13), because the stochastic stars include an excess (relative to the other light curve classes) of relatively early type stars ($\leq$K3). These early type stars will arrive on the ZAMS as A or F stars, and hence even on the PMS will have systematically higher rotational velocities than lower mass CTTS. The actual $v \sin i$’s, as illustrated in Figure 14, confirm this bias, with many of the most rapidly rotating stars in all three plotted CTTS groups having spectral type K3 or earlier. Excluding the early spectral types, the distribution of $v \sin i$’s for the three CTTS groups looks quite similar. The average $v \sin i$’s confirm this: the mean $v \sin i$’s for the three groups are $19.0 \text{ km s}^{-1}$ ($n = 10$), $20.8 \text{ km s}^{-1}$ ($n = 17$), and $18.7 \text{ km s}^{-1}$ ($n = 15$) for the stochastic, accretion burst, and variable extinction classes, respectively. The accretion burst mean is significantly influenced by one very discrepant star—Mon-7, with $v \sin i = 85 \text{ km s}^{-1}$, excluding Mon-7, the accretion burst class average $v \sin i$ becomes $16.9 \text{ km s}^{-1}$.

The essential equality of the mean $v \sin i$’s for the stochastic and variable extinction stars is perhaps unexpected. Given our conclusions concerning the line of sight inclination to the rotation axes of the two classes ($i \gtrsim 60^\circ$ for the variable extinction class and $i \lesssim 60^\circ$ for the stochastic class), and assuming a random distribution of inclinations within those ranges, one would predict $\langle \sin i \rangle_{\text{var-ext}} / \langle \sin i \rangle_{\text{stoch}} \sim 1.5$; hence for $\langle v \sin i \rangle = 18 \text{ km s}^{-1}$ for the variable extinction class, one would have expected $\langle v \sin i \rangle = 12 \text{ km s}^{-1}$ for the stochastic class. At face value, therefore, the equality of their average $v \sin i$’s suggests that the stochastic stars might be comparatively rapid rotators. However, because the mean value for the stochastic class was derived from only ten stars, we believe it prudent to simply conclude that it is unlikely that the stochastic stars are unusually slowly rotating.

### 5.4. Variability Timescales

One can obtain useful constraints on the timescale associated with accretion variability in the stochastic stars from our multi-epoch VLT/FLAMES spectra. If the accretion rate changed only slowly with time (e.g., with a several day time constant), then spectra taken on the same night, or on successive nights, would have lithium equivalent widths or He I 6678 Å fluxes that differ from each other by significantly less than spectra separated by several days. We have seven stars with multi-epoch VLT data (from either 2011 or 2013) where we can make this test using lithium, and four stars where this test is possible for the helium emission line (the other stars either never or rarely show helium emission). For each star, we identified time lags with at least three pairs of epochs with that time lag (often there were more than three). For each time lag, we calculated the mean absolute deviation between the measured equivalent widths for each pair of epochs. Figure 15 shows the time lag plots for lithium 6708 Å and helium 6678 Å. As an ensemble, the plotted data indicate that most of the variability occurs on timescales of order a day or less.

Photometric light curves, of course, provide a much more direct means with which to derive variability timescales. For stars with periodic light curves, one can easily determine that period and often associate that period with a physical mechanism (e.g., the rotation period of the star). For stars with aperiodic light curves, it is much more difficult to derive a timescale which correlates well with the shape one “sees” in the light curve and which can be convincingly linked to a physical mechanism. After some experimentation, we decided to derive timescale estimates based on an algorithm that measures how long it takes for the light curve to change by a given fraction of its full amplitude. Specifically, for every point in the light curve, the algorithm looks both forward and backward in time, and determines the time lag needed for the absolute difference in magnitude to change by a given amount. We then average the derived time lag for every light curve point to determine the mean time lag for that delta magnitude. We calculate those timescales for steps in delta magnitude ranging from 0.005 mag up to one half the full magnitude range in the light curve. When portions of the light curve seem to have linear trends in magnitude (only the first half of the Mon-425 light curve, and the last third of the Mon-795 light curve—see Figure 2 and Figure 3), we first detrend the light curve to remove that linear trend. We associate a characteristic time for the star as the derived mean time lag for a delta magnitude corresponding to half the full amplitude of the light curve\textsuperscript{23}. These characteristic timescales are provided in Table 2. The timescales range from half a day to of order five days, with most of the stars having

\textsuperscript{22} A brief description of our process for estimating $v \sin i$’s is provided in the Appendix.

\textsuperscript{23} This algorithm returns timescales that are quite similar to what would be derived from a peak-finding program, for peaks larger than half the full amplitude, but avoids the difficulty of determining when a peak occurs.
timescales near one day—in accord with the analysis of the VLT/FLAMES multi-epoch data.

In principle, the way in which the mean time lag depends on delta magnitude should encode information on the light curve shape. Figure 16 plots this relation both for our stochastic stars and for a comparison set of stars with periodic light curves. The plot shows nearly linear correlations for the periodic light curve stars, with all of the stochastic stars falling below that relationship. The stochastic stars with short characteristic timescales \((\tau < 1.2 \text{ days})\) in general fall closer to the periodic relation than the stochastic stars with longer characteristic timescales.

At a macroscopic level, it is reasonable to think of the light curves for the stochastic variables as reflective simply of a global accretion process whose \(dM/dt\) varies in a seemingly random way. Such light curves can be well-matched by simulations with a damped random walk process (e.g., Findeisen et al. 2015). However, on a microscopic level, it is possible that all of the variability arises from individual accretion events creating transient hot spots of variable size, temperature and lifetime. If so, the properties of the observed light curves could be used to place constraints on the properties of the individual accretion events. We have created a simple Monte Carlo process model to explore this idea.

Our model produces light curves of total duration 34 days, from which we extract the central 30 day portons (to minimize edge effects). We distribute \(N\) Gaussian flux bursts during the observing window, with each burst having a height, width and central epoch chosen randomly within specified bounds from a uniform distribution. We also add a continuum level to simulate the contribution to the light from the stellar photosphere. We vary the number of bursts and the parameter bounds (a) to match the observed light curve amplitudes; (b) to match the mean veiling (the fraction of the light from accretion compared to that from the photosphere); (c) to yield values of \(Q\) and \(M\) appropriate for stars with stochastic light curves; and (d) to yield timescales as judged from our \(\Delta m\) versus \(\Delta t\) algorithm that approximately match specific stochastic class stars.

Figure 17(a) shows a simulated light curve ("Case A") whose morphology, amplitude, mean veiling and timescale \((\tau = 1.4 \text{ days})\) was designed as a reasonable match to the CoRoT light curve of either Mon-346 or Mon-577 (see Figure 2). The parameters for this model were \(N\) (number of bursts in 30 days) = 300, FWHM = 0.2–0.7 days; height = 5.0–20.0 (in "counts"), and photospheric continuum level = 500 (in "counts"). \(M\) is 0.14 for this light curve, and the \(Q\) statistic indicates the light curve is random—hence \(Q\) is set arbitrarily to 1.

Figure 17(b) shows a simulated light curve ("Case B") whose morphology, amplitude, veiling and timescale \((\tau = 3.3 \text{ days})\) was designed to reasonably match the CoRoT light curve for Mon-457 (see Figure 2). The parameters for this model were \(N = 300\), FWHM = 0.9–2.7 days, height = 2.0–10.0, and photospheric continuum level = 400. \(M\) is −0.19 for this light curve, and the \(Q\) statistic indicates the light curve is random—hence \(Q\) is set arbitrarily to 1.

Figure 17(c) shows that as the frequency of bursts decreases, individual bursts become more visible and the light curve evolves to better resemble our accretion burst light curve class (Stauffer et al. 2014). The parameters for this light curve were \(N = 30\), FWHM = 0.5–1.5 days, height = 5.0–18.0, and photospheric continuum = 400.

Finally, Figure 17(d) provides a \(\Delta t\) versus \(\Delta m\) plot for the Case A and Case B models. Also plotted are the \(\Delta t\), \(\Delta m\) values for two idealized periodic light curves—a sine wave and a sawtooth function. The models designed to look like our stochastic stars have \(\Delta t\), \(\Delta m\) loci in the diagram that mimics the loci for the stochastic stars (Figure 16).

We view this exercise as primarily a proof of concept. The stochastic light curves can indeed be simulated with many small, discrete flux bursts. There must be many bursts, on average, per day in order to yield light curve shapes that appear symmetric about their median value. However, the durations of the events must be kept short in order that the summed flux from the accretion events does not become too large and the light curves do not become too smooth (low amplitude). The parameters we have chosen for Case A and B are presumably not unique, but they at least provide possible choices that could yield light curves similar to those we observe in NGC 2264.

5.5. Correlation of Optical and IR Light Curves

The optical photons from CTTSs come primarily from the photosphere and the hot spots produced by accretion shocks. The IRAC (3.6 and 4.5 \(\mu\)m) photons also originate from these regions, as well as from warm dust in the inner circumstellar disk. For stars with only small IR excesses from warm dust, and where there is little or no variable extinction, the optical and IR light curves should be well-correlated (but possibly with significantly different amplitudes), regardless of the physical mechanism driving the variability. For stars where the disk photons dominate at IRAC wavelengths, the optical and IR light curves could be quite uncorrelated, depending on the physical mechanisms involved. The most likely physical processes driving variability at IRAC wavelengths are: (a) heating of the dust in the inner disk by reprocessing of the photons emitted from the star’s surface; (b) changes in the inner disk dust surface area exposed to the stellar photon bath (e.g., from instabilities lifting more dust into the disk photosphere); and (c) viscous, self-heating of the inner disk. The optical–IR correlation can also be affected by details of the geometry—a transient hot spot on the side of the star facing us produces a flux burst most evident in the optical light curve, but if that hot spot is not located in a position where it is seen by the warm dust that dominates the IRAC light, then it may have only a minor impact on the IRAC light curve. Conversely, a transient flux burst on the back side of the star would have no impact on the optical light curve that we see, but could have a significant impact on the IR light curve if the IR flux is dominated by photons from warm dust in the inner disk wall that faces the back side of the star, as is in fact likely. As discussed extensively in Whitney et al. (2013), the correlation between the optical and IR light curves of the stochastic stars therefore can provide important clues to the physics underlying their variability; we discuss that correlation for our stochastic stars now.

Table 2 provides two quantities related to the optical/IR variability issue—the estimated disk to photosphere flux ratio at 4.5 \(\mu\)m (column 6), derived from our single-epoch photometry obtained prior to 2010, and an optical-to-IR Stetson index (column 8), derived from our 2011 CSI 2264 campaign data. The disk to photosphere ratio ranges from 0.4 for Mon-242, a star with very little IR excess, to >10 for Mon-985, a
star with a very large IR excess. The Stetson index (see Cody et al. 2014 for a more thorough discussion) ranges from 0.41 (largely uncorrelated) to >2 (well-correlated). Figure 18 shows an overlay of the CoRoT and IRAC light curves for four of the stochastic stars where the Stetson index indicates a good degree of correlation between the optical and IR light curves.

The stars in Figure 18 are arranged in order (top-left to bottom-right) of increasing disk dominance at 4.5 \( \mu \)m, with disk-to-star flux ratios of 0.4, 2.9, 5.4, and >10 for Mon-242, 119, 636, and 985, respectively. Visual examination of the four panels indicates that they are also arranged approximately in order of the degree to which the amplitude and shape of the short-timescale IR fluctuations match those in the optical. The optical and IR light curves for Mon-242 track each other very well on short timescales in both shape and amplitude. Mon-119 generally shows well-defined IR peaks at location of the optical peaks, with amplitudes often of order half that as shown in the optical. Mon-636 and Mon-985, both having disk-dominated IRAC photometry, show much lower amplitude variability in the IR compared to the optical, but often appear to have barely discernible features at the location of structures in the optical light curve. A better view of the optical–IR correlation for these two stars is provided in Figure 19, where the IRAC light curves are shown magnified by a factor of 3 in the y-axis. This plot shows that, in fact, there is still a good correlation in the optical and IR short-timescale morphology, but the amplitudes of the IRAC peaks are on average about one third the amplitude of the optical peaks.

Close examination of the four panels of Figure 18 shows some optical features which appear to be completely lacking in IR counterparts. Good examples are flux excesses in the optical light curve for Mon-119 at days ∼12 and ∼20, with no evidence at all for a feature at those times in the IRAC light curve. There are no obvious inverse situations, where an isolated IRAC flux peak is lacking a simultaneous CoRoT peak.

Assume for the moment that the accretion hot spots have effective temperatures of order 8000 K and that our CTTS are all around spectral type K4. If the hot spot emitted as a blackbody, it would have \( R \sim [3.6] \sim 0 \), and the “quiescent” photosphere would have \( R \sim [3.6] \sim 2 \). In the absence of any warm dust, an accretion burst causing a 0.2 mag brightening in the optical light curve (comparable to the light curve amplitude for a typical stochastic star) would cause only a ∼0.03 mag brightening at 4 \( \mu \)m. For stars with large IR excess, where the disk dominates the 4 \( \mu \)m flux by a large factor, the flux variation at 4 \( \mu \)m directly from the photosphere would be even lower. Because the emitted flux from accretion hot spots has a spectral shape closer to \( F_\lambda \sim \lambda^{-1} \) constant rather than a blackbody spectrum (Hartigan et al. 1989; Basri & Batalha 1990), this estimate is somewhat inaccurate, but we believe the basic conclusion is still valid. Therefore, it is unlikely that the flux variation at IRAC wavelengths seen in any of the stars in Figure 18 is directly a result of the variable photospheric contribution.

Assume now also that radiative heating dominates the energy budget for the warm dust responsible for the flux at IRAC wavelengths, and also assume that the system geometry is such that the transient hot spot is well positioned to be seen by us and by the warm dust in the inner disk. In that case, a change in the luminosity of the star of \( \Delta m(\text{bol})_\text{star} \) due to appearance of a transient hot spot should approximately result in a similar increase in the luminosity of the warm dust. A 8000 K hot spot should have an SED peaked near 4000 Å, close enough to the center of the broad CoRoT bandpass such that a 20% change in the CoRoT light curve flux should correspond approximately to a 20% change in luminosity of the hot spot. For 1000 K dust, \( \lambda_{\text{max}} \sim 4 \mu \)m, and a 20% change in the IRAC light curve should correspond approximately to a 20% change in the luminosity of the warm dust. This suggests that there could be a good correlation between optical and IR light curves for stars with disk-dominated fluxes at IRAC wavelengths, which we in fact see (Figure 19). To be explained still are the variable, and sometimes small IR-to-optical amplitude ratios, and the optical peaks with no apparent IR counterpart.

It is possible to adjust the geometry to reduce the response of the disk to the hot spot luminosity variations by placing the hot spots at higher stellar latitude. This reduces the projected area of the hot spot as seen by the inner disk dust roughly as the cosine of the spot latitude, so that a spot at 70° latitude would have about half the disk heating impact of a spot of the same physical size if at 45° latitude. For an observer located near the rotation axis of the star, spots at such high latitudes would always be visible and the portion of the inner disk-rim they “light up” should have similar view angles to the observer—which would result in a good correlation between the optical and IR peaks and a rarity of cases where there is an optical peak without an IR counterpart. As either the spot latitude decreases or the inclination of the observer’s line of sight to the system
rotation axis increases, the chance for a transient hot spot occurring where it is not visible to the observer increases. Therefore, the observed correlation between the optical and IR light curves favors both relatively high spot latitudes and relatively low inclinations of the system rotation axis to our line of sight. This geometry also naturally reduces any periodic signature in our light curve due to the star’s rotation.

6. SUMMARY AND CONCLUSIONS

Based on the preceding sections, we can summarize the properties that characterize stars whose optical light curves fall into our stochastic class as follows.

1. By selection, their optical light curves appear symmetric about their median level, with no preference for discrete downward flux dips (variable extinction) nor upward flux bursts (short-duration flux bursts). The lack of flux dips due to extinction excludes stars where the inclination of our line of sight to the circumstellar disk is large, implying $i \lesssim 60^\circ$.

2. By selection, their optical light curves show very little periodic signature.

3. The fraction of the CTTS in NGC 2264 having optical light curves of this type is about 10%.

4. As judged by their UV excesses, H$\alpha$ equivalent widths, and veiling of optical absorption lines, the stars with stochastic light curves have relatively low to moderate accretion rates. Their mean veiling level is generally of order 10%–20%.

5. Their CoRoT light curves show amplitudes generally in the range of 10%–30%.

6. In all cases, their broad-band IR photometry indicates SED slopes consistent with Class II.

7. The members of the stochastic light curve class have spectral types ranging from early G to early M, with a somewhat earlier mean spectral type than our other CTTS light curve classes.

8. The stochastic stars have small reddening, as judged from the $J - H$ versus $H - K$ color–color diagram and from comparison of their observed optical colors to colors predicted based on their spectral types.

9. Their H$\alpha$ profiles are most often characterized by blueshifted absorption dips that are usually present with similar shape and amplitude at all epochs, best explained as due to gas in a disk wind seen from moderate to low inclination angles.

10. They have veiling variability and color changes derived from multi-epoch photometry indicative of a variable blue continuum source, consistent with expectation for photospheric hot spots whose size or temperature change with time.

11. Variability timescales for the stochastic stars derived either from the light curves or from multi-epoch spectroscopy are generally of order 1–2 days.

12. There is usually a good correlation between the optical and IR light curve morphologies on short timescales, but often much lower amplitudes for the IR fluctuations; short timescale events at one wavelength but not the other are quite rare. These characteristics are best explained by placing the transient hot spots at high stellar latitudes and the observer at low inclination angles to the star system rotation axis.

Figure 15. (a) Mean absolute difference for lithium equivalent widths measured at two different epochs as a function of the time lag between the two epochs. (b) same as for (a), except the feature measured is the narrow emission component for He I 6678 Å.
Our data show that the light curve variability of the stochastic class arises from their having highly variable photospheric mass accretion. Of course, all CTTS presumably have variable mass accretion rates. For some CTTS, most notably the variable extinction light curve class, other processes produce fluctuations in the optical flux of much larger amplitude which mask the comparatively small changes in brightness due to the variable accretion rate. Where such camouflage is not present, there appears to be (at least) three light curve morphologies where accretion processes drive the variability. Stars with one or two dominant, stable accretion flows (funnel flow accretion) where the star’s rotation is the dominant timescale can produce quasi-periodic, symmetric (“hot spot”) light curves (Cody et al. 2014), like that shown in Figure 1(e). Stars with the highest accretion rates have light curves dominated by relatively strong, short-duration accretion bursts that are usually random in time but sometimes occur as periodic burst groups (Stauffer et al. 2014; Blinova et al. 2015). What is the physical driver for the variability shown by the stochastic light curve class?

We believe a clue to the answer to this question can be found by considering the members of the variable extinction class, and in particular one of the prototypes—AA Tau. Based on an extensive Zeeman Doppler imaging study of AA Tau, Donati et al. (2010) concluded that (a) its magnetic dipole axis is tilted by \( \sim 20^\circ \) relative to its rotation axis; (b) the primary accretion hot spots are located near latitude \( \pm 70^\circ \); (c) its mean mass accretion rate to the stellar surface is quite small, with veiling levels ranging from near zero up to \( \sim 0.2 \); (d) that the accretion rate varies significantly on timescales less than the stellar rotation period. Concerning the variability in the inferred accretion rate, they also concluded that “... the accretion variability observed for AA Tau mostly relates to the variable efficiency at which the disc material succeeds at entering the closed magnetosphere in the propeller regime, rather than to an intrinsic variability of the accretion rate within the inner disc.”

This characterization of accretion in AA Tau very nearly matches our description of accretion in the stochastic light curve class, and we believe this points to the most likely physical model for their variability. Our line of sight to the variable extinction class members must be \( i \gtrsim 60^\circ \). There must be at least as many CTTS with the same accretion properties but seen at \( i \lesssim 60^\circ \). Our data support identifying at least many of these low-inclination counterparts to the variable extinction class stars with members of the stochastic light curve class. Adopting the Donati et al. (2010) conclusion for AA Tau, we suggest that instability processes in the disk photosphere regulate the flow of material onto the magnetic field lines in the funnel flow, thereby also leading to the stochastically variable flux from hot spots on the stellar surface. Some fraction of the variable extinction stars may have more stable accretion and hence have hot spots that are relatively stable in size and location; when seen at moderate inclination, these stars should have light curves that are more or less periodic. Cody et al. (2014) labeled such stars as quasi-periodic, symmetric. Future synoptic studies of star-forming regions should be conducted to determine whether stars with quasi-periodic, hot-spot light curves can transition to the stochastic light-curve morphology (and, if so, how the statistics for that transition compares to the statistics for the transition between AA Tau type light curves and the aperiodic flux dip light curve class).

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Facilities: Spitzer (IRAC), CoRoT, CFHT (MegaCam), VLT (FLAMES).
APPENDIX

A.1. CoRoT Light Curves for Additional Stars Whose QM Metrics Match that for Stars with Stochastic Light Curves

We have used two methods to assign stars to the stochastic light curve class, with each method having its own uncertainties. One method uses quantitative formulae to derive metrics for the light curves (Cody et al. 2014); however, the formulae are empirical and the boundaries are to some extent arbitrary. The other method is entirely qualitative and is based on “by eye” classification of the light curves by sorting them into groups which seem to have similar properties. The light curves shown here in Figure 20 match the algorithmic definition to be in the stochastic light curve class, but did not pass our “by eye” classification scheme. They therefore are not included in our final list of stars with stochastic light curves (Table 2). See discussion in Section 3.

Figure 17. Results from Monte Carlo models aimed at simulating the light curve morphologies of the stochastic light curve class. See discussion in Section A.3. The photospheric continuum level in plots (a)–(c) are 13.25, 13.49 and 15.0 mag, respectively. (a) Simulated light curve intended to emulate the morphology of a short timescale stochastic star (e.g., Mon-346 or Mon-577); (b) Simulated light curve intended to emulate the morphology for a long timescale stochastic star (e.g., Mon-457); (c) Simulated light curve, intended to emulate a light curve we would classify as accretion-burst dominated (Stauffer et al. 2014); (d) $\Delta t$ vs. $\Delta m$ plot for the light curves in panels (a) and (b), compared to two idealized light curve types (sine wave and sawtooth).

A.2. Spectral Feature Variability and Light Curve Morphology

In Section 4.1, we showed that when we had appropriate synoptic high-resolution spectroscopy, the stars with stochastic light curves have veiling levels which vary with time and are quantitatively consistent with the observed photometric variability. We also showed that the Li I 6708 Å doublet—the strongest absorption feature in our spectra—can be used as a veiling indicator (because its equivalent width variations correlate well with the equivalent width variations of other absorption features in our spectra) and that the variations in the lithium equivalent widths also correlate well with variations in the strength of the He I 6678 emission line.

In this section, we wish to show that these same spectral features can also be used as diagnostics of the physical processes underlying the variability for other light curve classes. For this purpose, we have selected six stars with disparate light curve morphologies and for which (a) the
**CoRoT** light curve amplitude in 2011 is at least 0.10 mag (in order to be comparable to the typical amplitudes for the stochastic stars and in order to ensure a strong signal in our spectral indices if variable accretion drives the light curve morphology) and (b) we have multi-epoch VLT/FLAMES spectra in 2011. These six stars include (1) a WTTS with a periodic, stable light curve morphology which we attribute to cold spots; (b) a CTTS having a periodic light curve which we would also normally attribute to cold spots; (c) two CTTS whose **CoRoT** light curves show quasi-periodic structures which we attribute to hot spots; and (d) two CTTS whose **CoRoT** light curves have unusual morphologies which do not obviously align well with our standard light curve classes. Figures 21 and 22 show the **CoRoT** light curves, the correlation between lithium equivalent width and HeI 6678 Å, and the correlation between lithium equivalent width and the equivalent width of other relatively strong absorption features in our echelle order.

For these plots, as well as all the other similar plots in this paper, we have utilized sky-subtracted spectra. That is, for each object fiber, we have found the nearest sky fiber (which could be up to a few arcminutes away) and subtracted the latter from the former. Due to the spatially varying nebulosity, this is a necessarily imperfect process. For the absorption line and HeI emission line measures of most interest here, sky subtraction primarily is needed in order to minimize any contribution from scattered moon light. The 2013 spectra were taken almost entirely during a dark run, and therefore the sky fiber continuum levels are very low and the uncertainty in sky correction has very little possible impact. For 2011, however, spectra were taken at all lunar phases, and the sky continuum level varies significantly and so could impact equivalent widths for faint stars. This is probably the largest source of uncertainty in our plots, though we believe it should not impact any of our conclusions. For the HeI 6678 Å equivalent width, an additional source of uncertainty is that there is an FeI absorption feature almost coincident in wavelength with the HeI line, and whose strength is not negligible with respect to the HeI line we normally see. We have corrected our measured HeI equivalent widths for this FeI feature by measuring the strength of the latter line in WTTS as a function of spectral type, and then subtracting this amount from the measured HeI equivalent width.
The FeI equivalent widths range from 0.15 Å at G2, increasing to about 0.26 Å at M0, and then decreasing to 0.12 Å at M2.

The plots for Mon-1274 (WTTS) and Mon-103 (CTTS) show these stars have little or no veiling variability despite CoRoT light curve amplitudes of ~0.2 mag. The rightmost plot for each star shows that HeI 6678 is not in emission. The similar properties for the two stars indicates that cold spots can dominate the light curve morphology of CTTS, as has been advocated previously (e.g., Herbst et al. 1994). The dispersion in the plotted points for the center and right-hand side (rhs) plots for these two stars is primarily due to measurement uncertainties.

The CoRoT light curves of Mon-168 and Mon-370 (both CTTS) were selected on morphological grounds as candidates for rotational modulation of hot spots whose size/temperature vary significantly over the CoRoT campaign duration. This results in semi-sinusoidal waveforms that are more structured than in the case of cold-spots and also are less stable in time. The spectral indices plots confirm that these stars have variable veiling and HeI in emission, and that the absorption line veiling and HeI emission are correlated. We therefore confirm that hot spots are the driver of the CoRoT light curve morphology, and the period derived for these stars is the photospheric rotational period.

Finally, Mon-498 and Mon-1199 (also both CTTS) have CoRoT light curves whose morphology are unusual and not completely consistent with any of our light curve classes. The center plot for these two stars (lithium versus “other” absorption line equivalent widths) shows no significant correlated variability, and hence no firm evidence for accretion variability. The rhs plots do show a possible correlation between the lithium equivalent width and HeI 6678 Å. However, the inferred extra continuum flux would only be ~5%-10% of the stellar photosphere, thus only about half of the CoRoT amplitude for Mon-498 and only a very small fraction of the CoRoT amplitude for Mon-1199 could be attributed to accretion variability. Instead, we suspect that cold spots plus one or more short-duration flux dips due to variable extinction (at day 5906 and possibly day 5930) best explain the light curve for Mon-498. The lack of veiling variability and the quite large amplitude of the photometric variations for Mon-1199 argue that its light curve variations are primarily due to variable extinction arising from MRI or other instabilities in its inner circumstellar disk temporarily lofting more dust into the disk photosphere.

Figure 19. Overlay of the CoRoT and Spitzer light curves for Mon-636 and Mon-985, where in this case the y-axis full-scale for the IRAC data is one third that for the CoRoT data (e.g., for Mon-985, full scale for the IRAC data is 0.4 mag, whereas it is 1.2 mag for the CoRoT data). A slowly varying baseline has been subtracted from the Mon-636 CoRoT data in order to better visualize the short-timescale correlation of the optical and IR light curves.
Stars whose light curves are dominated by deep flux dips produced by variable extinction events form another common CTTS light curve class. These flux dips can either be periodic (like AA Tau), and likely due to our line of sight being occulted by a warp in the inner circumstellar disk, or aperiodic, and possibly due to instabilities temporarily lifting more dust into the upper layers of the inner disk. Many stars appear to cycle back and forth between these two light curve morphologies on long (year or years) timescales (McGinnis et al. 2015). Based on their UV excesses, mean veiling and H\(\alpha\) equivalent widths, these stars have similar mean mass accretion rates as the stochastic light curve class members, and therefore we might expect similar veiling variability. We have investigated this by measuring the absorption line equivalent widths for eight of the variable extinction stars; Figure 23 shows plots of the correlation between Li\(\text{I}\) 6708 equivalent width and the other absorption lines (plotted in the same way as was done for the stochastic stars in Figure 8) for four of these stars. In summary, we find that the AA Tau and aperiodic flux dip stars show a range of accretion variability. The data for the two AA Tau stars with the largest measured veiling variability (Mon-811 and Mon-1037) are shown in the top of Figure 23. At the bottom of Figure 23, we show plots for two of the McGinnis et al. (2015) stars that show essentially undetectable veiling variability (\(<5\%\) variation in the lithium equivalent width). Most of the variable extinction stars in fact show undetected or barely detected (\(<10\%\)) variations in their veiling levels. This emphasizes that their large light curve amplitudes (often more than 0.5 mag, peak to peak) must be driven by some process other than variable accretion.

### A.3. H\(\alpha\) Profiles for the Stochastic Stars

Our VLT/FLAMES spectra only have a wavelength coverage of about 350 Å. In the echelle order, we have only two lines normally in emission for CTTS are present—H\(\alpha\) and He\(\text{I}\) 6678 Å. For eight of the stochastic stars, we have multi-epoch data with either 12 or 20 spectra, depending on the year. In Figure 12, we overplot the entire set of profiles for two of the stars with multi-epoch data. Here (Figure 24), we provide single epoch H\(\alpha\) profiles for “representative” profiles for each of the stars for which we have VLT/FLAMES spectra.
we have multi-epoch data, we have tried to choose an epoch which shows features which are present in the majority of the epochs.

A.4. Spectral Types Used in Figure 13

In Table 5 we provide the spectral types used to construct the spectral type histograms for the accretion burst, variable extinction and short-duration flux dips classes shown in Figure 13. The spectral types for the stochastic class are provided in Table 2. For all four groups, where possible we use published spectral types, as described in Cody et al. (2014). For a few of the short-duration flux dip stars, we have derived spectral type estimates from our own spectra (Stauffer et al. 2015). Where actual spectral types were not available, we have estimated spectral type by adopting the estimates for stellar luminosity and radius described in Venuti et al. (2014); combining those two quantities and the Stefan–Boltzmann law to estimate the effective temperature of the star; and then using the spectral type to \( T_{\text{eff}} \) conversion for young stars provided in Pecaut & Mamajek (2013). We also provide H\( \alpha \) equivalent widths for the variable extinction and accretion burst members in the table, because those numbers are used in Section 3. The H\( \alpha \) data are generally

Figure 21. CoRoT light curves and spectral indices plots for three NGC 2264 members: (a) Mon-1274, a WTTS with a typical cold-spot light curve; (b) Mon-103, a CTTS with a cold-spot light curve; and (c) Mon-168, a CTTS with a hot-spot light curve (see text). In the middle plot in each row, the different colors correspond to different absorption features; also, the individual equivalent widths have been divided by the maximum equivalent width measured for that feature, in order to allow multiple features to be over-plotted.
from the literature (Cody et al. 2014); when no literature value was available, we have measured representative H\alpha equivalent widths from our own VLT spectra, from the ESO-Gaia spectra, or from MMT Hectochelle spectra described in Furesz et al. (2006).

A.5. Derivation of Projected Rotational Velocities (v sin i’s) from the VLT Spectra

We have derived v sin i estimates in two ways for the CTTS in NGC 2264 for which we have VLT/FLAMES spectra. Our initial v sin i estimate begins by co-adding all epochs of spectra for each star to produce a high S/N mean spectrum. For the adopted spectral type for each star, we produce a synthetic spectrum at the FLAMES spectral resolution, and then convolve that spectrum with a rotational broadening function, using software routines available in SME (Valenti & Piskunov 1996), Synth3 and Binnmag3 (Kochukhov 2007). We do this for a range in adopted rotational velocities, and compare the model spectra to the observed spectrum in a least-squares sense. The v sin i we adopt is that for the model whose spectrum matches most closely the observed spectrum. The formal uncertainties in the derived v sin i’s are generally 2–3 km s\(^{-1}\). We note that the model spectra assume solar abundance, hence essentially no feature is present for the lithium 6708 Å doublet; these v sin i’s therefore are based on all the other absorption features in the FLAMES H\alpha order.

After deriving v sin i’s in this manner for all of our NGC 2264 CTTS, we plotted those v sin i’s versus the mean FWHM of the lithium 6708 Å doublet for each star (i.e., we measured the FWHM at each epoch, and then took the average of those values; the FWHM for the stochastic stars ranges from 0.7 to 1.8 Å, with rms for the dozen or more epochs for a given star of order 0.03 Å). The plot shows the expected relationship, but with a larger than anticipated scatter for stars with small v sin i. As one approaches the resolution limit of the spectrograph, one of course expects an increase in scatter, but it was also possible that by averaging spectra for the v sin i analysis we could artificially broaden lines (e.g., for an SB1). Therefore, we adopted a second procedure to estimate v sin i based on combining the lithium FWHM data and the original v sin i data to provide a calibration. For this purpose, we fit a calibration curve to the plot of v sin i versus FWHM. Then, for each star, we used that calibration curve and the measured mean lithium FWHM to provide a new v sin i estimate. Because the lithium 6708 Å line is always the strongest absorption feature in these spectra, for faint and/or slowly rotating stars, this latter v sin i estimate could be more reliable than the initial estimate. Table 4 provides both v sin i estimates—column 7 provides the initial v sin i estimate, and column 8 the v sin i estimate derived from the measured lithium FWHM.

Comparison of the two v sin i estimates in Table 4 shows generally good correspondence. However, a few stars show...
significant differences, with Mon-1234 having the most significant discrepancy (24.0 versus 15.9 km s\(^{-1}\)). The spectral synthesis method yields essentially the same \(v\sin i\) for Mon-636 and Mon-1234, while the lithium FWHM method yields 24.9 and 15.9 km s\(^{-1}\), respectively. The mean and rms FWHM for the two stars are 0.827 ± 0.036 and 0.725 ± 0.024, respectively, with none of the Mon-1234 FWHM values being as large as the smallest FWHM measurement for Mon-636. The lithium widths preclude these stars from having the same \(v\sin i\). Based on this and similar comparisons, we adopt the \(v\sin i\)'s derived from the lithium width as our best estimates of \(v\sin i\), and we use those estimates in the plots in the main body of the paper.
Figure 23. Correlation between the equivalent width for the Li I 6708 Å doublet and other absorption lines present in the same FLAMES echelle order, for four CTTS whose CoRoT light curves are dominated by variable extinction events. The equivalent widths at each epoch have been divided by the maximum equivalent width for that feature, in order to allow data for several features to be over-plotted. The top two panels show stars with strong veiling variability; their He I 6678 emission line equivalent widths also vary and are well-correlated with the variations in the veiling levels from the absorption features. The bottom two plots show two stars with similar CoRoT light curve morphology, but where there is no detectable veiling variability.
Figure 24. Hα profiles of the stars whose CoRoT light curves are categorized as stochastic, for those stars for which we have available high resolution spectra. The vertical dashed red line marks rest velocity for Hα. We omit an Hα profile for Mon-613 here (to make the figure more compact)—our multi-epoch Hα profiles for this star are shown in Figure 12.