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PERIODIC PHOTOMETRIC VARIABILITY IN THE BECKLIN-NEUGEBAUER OBJECT

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ABSTRACT

The Becklin-Neugebauer (BN) object in the Orion Nebula Cluster (ONC) is a well-studied optically invisible, infrared-bright young stellar object, thought to be an intermediate-mass protostar. We report here that BN exhibited nearly-sinusoidal periodic variability at the near-infrared H- and K_s-bands during a one month observing campaign in 2000 March/April. The period was 8.28 days and the peak-to-peak amplitude ∼0.2 mag. Plausible mechanisms for producing the observed variability characteristics are explored.

Subject headings: infrared: stars — stars: individual (BN) — stars: pre-main sequence — stars: variables -

1. INTRODUCTION

The BN object was revealed during early raster scanning of the Orion Nebula region at 2μm, and immediately recognized as a candidate protostellar object (Becklin & Neugebauer 1967). BN is the brightest at near-infrared wavelengths of a group of ∼20 intermediate- and high-mass young stars and protostars in OMC-1. These objects were discovered at mid-infrared (Rieke, Low, & Kleinman 1973; Downes et al. 1981; Lonsdale et al. 1982; Dougados et al. 1993; Gezari, Backman, & Werner 1998), radio (Churchwell et al. 1987; Felli et al. 1993; Menten & Reid 1995), and x-ray (Garmire et al. 2000) wavelengths. The total luminosity emanating from the embedded cluster is $\sim 10^5 L_\odot$. In addition to its luminous point sources, the BN region is also notable as the source of the spectacular H_2 "fingers" or "bullets" (Allen & Burton 1993) which extend several arcminutes to the northwest and southeast.

BN itself is extinguished by A_V = 17 mag and has luminosity 2500 $L_\odot$ (Gezari et al.) corresponding to a main sequence B3-B4 star. It was the first of a still small class of young, mostly luminous, stars with the 2μm CO bandheads in emission (Scoville et al. 1979, 1983). These $\Delta\nu$=2 transitions are thought to arise from collisional or shock excitation in a hot, dense region, perhaps the inner part of a circumstellar disk or wind. BN also has relatively strong H_2 (Scoville et al. 1983) and weak Hu, Pf, and Br hydrogen recombination lines (e.g. Bunn, Hoare, & Drew 1995). Broad absorptions at 3.3μm and 10μm are due to circumstellar ice and dust (Gillett & Forrest 1973).

2. PHOTOMETRIC MONITORING OBSERVATIONS

Time series photometry at J, H, and K_s was acquired using the 2MASS southern telescope at Cerro Tololo during gaps in right ascension not otherwise utilized near completion of the 2MASS survey. As described in Carpenter, Hillenbrand & Skrutskie (2001), 29 sets of photometry were obtained over an area $<\sim 0.84^\circ \times 6.0^\circ$ centered on the Trapezium region of the ONC. Observations were conducted on nearly a nightly basis between 2000, March 4 and April 8 with BN observed on 28 of these nights. In addition to these specially scheduled observations, BN was observed twice during normal 2MASS survey operations on 1998, March 19 and 2000, February 6.

As detailed in the 2MASS Explanatory Supplement (Cutri et al. 2000), the image data consist of doubly-correlated differences of two NICMOS readouts separated by the 1.3s frame integration time. The first readout occurs 51ms after reset and independently provides a short integration to recover unsaturated images of bright (5-9 mag) stars. Each position on the sky is observed 6 times in this manner as the telescope scans in declination. For BN, the photometric measurements at K_s-band are derived from the 51ms integrations since the source saturates in the 1.3s images. Magnitudes are obtained using aperture photometry with an aperture radius of 4″ and a sky annulus extending radially from 24″-30″. The final magnitude is the mean of the six aperture magnitudes, and the photometric uncertainty is the standard deviation of the mean of the six measurements. At H-band, BN is faint enough that the magnitudes normally would be estimated with Point Spread Function (PSF) fitting on the 1.3s images. However, since BN is located on an extended plateau of bright nebulosity, the PSF fit converged for only 1 of the 28 sets of observations. Therefore, we report aperture magnitudes at H-band as well, computed with an aperture radius of 4″ and a sky annulus extending radially from 14″-20″. BN was not measured reliably at J-band.

Except for the time series aspect, the dataset, as produced by IPAC, is identical in format to that produced for the 2MASS survey itself, containing position, photometry, photometry error, and photometric quality flags. To improve the photometric accuracy within the time series data a grid of bright, isolated stars with low night-to-night variations was defined over the full $\sim 0.84^\circ \times 6.0^\circ$ survey region and used as internal standards to adjust the nominal 2MASS calibration zero points on a nightly basis. Typical zero point corrections were < 0.015 mag. The details of this procedure and all other processing and analysis steps are described in Carpenter et al.

3. VARIABILITY CHARACTERISTICS OF BN

For all of our ∼18,000 point sources, we looked for photometric variability by comparing the observed brightness changes in time to those expected according to the formal photometric uncertainties. To quantify the likelihood that variability occurred within the timespan of the observations we employed both a χ^2 technique and a method developed by Welch

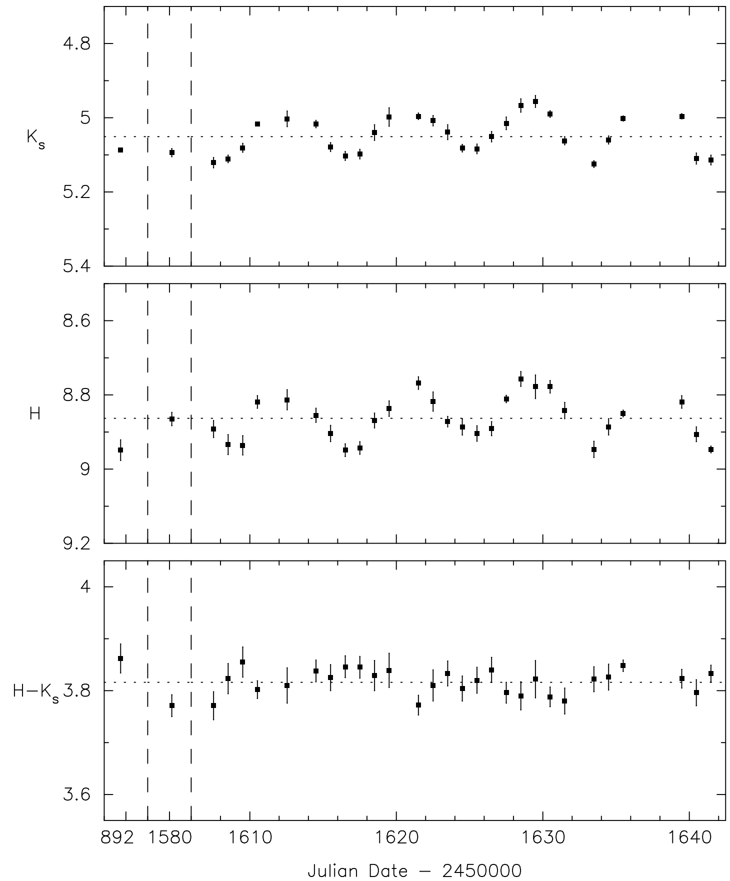

FIG. 1.— Lightcurves in K_s-band, H-band, and H-K_s color for BN as seen by the 2MASS southern telescope in 2000 March/April. Dotted line is the mean magnitude over this time interval. The first two data points were taken during normal 2MASS survey operations and are disjoint from the rest of the data stream.

& Stetson (1993) and Stetson (1996) which looks for correlated variability between multiple photometric bands.

The BN measurements exhibited ${\chi_\nu}^2(K_s)$ = 21, ${\chi_\nu}^2(H)$ = 13, and a Stetson-J variability index of 3.1 (where we have considered values of $\chi^2_\nu > 1.5$ and Stetson-J > 0.55 in Carpenter et al. to identify variables). Lightcurves appear in Figure 1 and the data in Table 1. The mean magnitudes of BN during the 2000 March/April time period were H = 8.87 and K_s = 5.04. The error-weighted root-mean-squared of the measurements, which are proportional to the variability amplitudes, were 0.06 mag at H and 0.04 mag at K_s compared to typical photometric uncertainties of $<$0.02 mag. The observed peak-to-peak amplitudes, neglecting errors in the photometry, were 0.26 at H, 0.17 at K_s, and 0.13 at H-K_s.

For BN the lightcurve is clearly periodic, and application of the Lomb-Scargle algorithm from Press et al. (1992) yields a period of 8.28 days at both H and K_s (analyzed separately) with false alarm probabilities (FAP) of $<$0.1%. The error in this period according to the Kovacs (1981) formula for frequency shifts in fourier analyses, is 0.05 days. We show the periodograms in Figure 2 and the phased lightcurves in Figure 3. The H-K_s color may also be periodic with the same oscillation as the H and K_s fluxes; however, this period is not significant (FAP = 38%). Color variations are such that H-K_s is redder when the star is fainter, in the proportions expected from a standard extinction law.

Returning to Figure 1, in addition to the periodicity, there is a brightening of the magnitudes by $\sim$0.1 mag at H and $\sim$0.05 mag at K_s over the first three cycles of the period which is more apparent once the sinusoidal behavior is subtracted. Yet the faintest point at the end of the third cycle and the last two points in the data stream at the end of the fourth cycle are all too faint to support that this apparent rise is a long term behavior. Further, the 2000 February and 1998 March flux levels indicate that this recent brightening trend did not originate much before the beginning of the 2000 March/April time series.

4. INTERPRETATION AND DISCUSSION

Given the protostellar nature of BN, it is worth considering the physical origin of the 1.6-2.2μm flux (the shortest wavelengths at which BN has been detected). Assuming the B3-B4 spectral type and 17 mag of visual extinction from Gezari et al., the H-band magnitude matches within a few tenths that predicted for a reddened stellar photosphere. We take this as minor evidence that the H-band photometric variability may arise close to the photosphere. At K_s-band, however, the (dereddened) magnitude is almost 4 mag above the predicted photosphere. The hot dust and/or gas producing the 2.2μm excess must subtend an area larger than that predicted by a standard blackbody disk or shell model since all close-in grains are destroyed by stellar heating. Accretional heating is one way to do this. That the K_s-band magnitude is dominated by circumstellar flux suggests, alternately, that the variability may occur in the dust envelope. Despite these differences between H and K_s in the ratio of non-photospheric to photospheric flux, the observed periods are the same with the ratio of period amplitudes consistent with reddening.

Periodic variable stars have been studied optically in the ONC region by Herbst et al. (2000, and references therein), Stassun et al. (1999), and Rebull (2001). Almost all stars identified as periodic in these unbiased studies have been low mass, $< 2M_\odot$. Only one periodic variable earlier than mid-

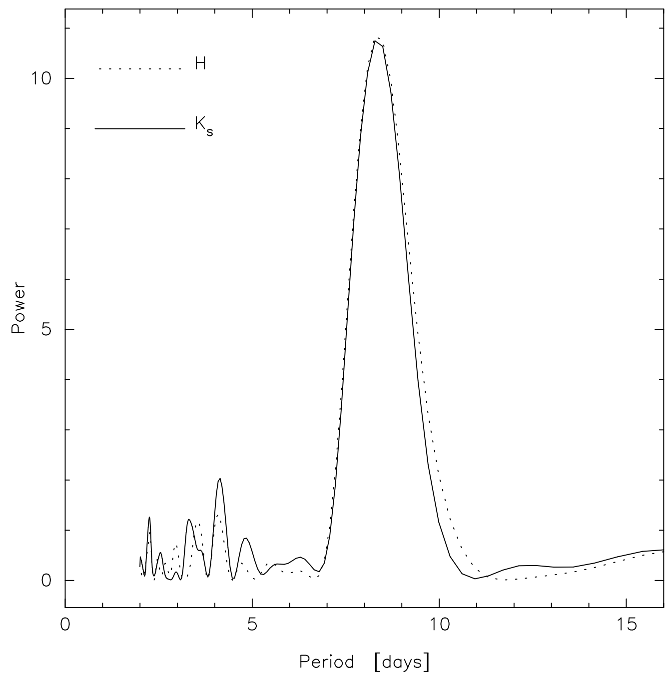

FIG. 2.— Periodogram for H- and K_s-band data. The most significant peak at 8.28 days has a false alarm probability in the Lomb-Scargle formalism of $<0.1\%$.

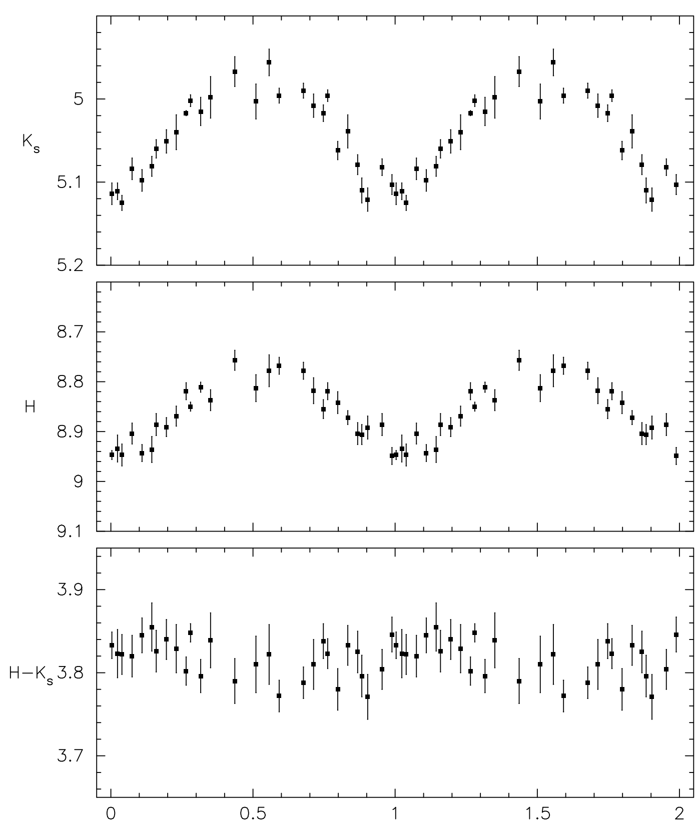

FIG. 3.— K_s-band, H-band, and H-K_s lightcurves phased with a period of 8.28 days. Two full phases are shown.

G has been found, JW660 with a mid-B spectral type and a mass $\sim 6M_\odot$ (Hillenbrand 1997). The period of 6.15 days reported by Mandel & Herbst (1991) has, perhaps notably, not been found again in subsequent observing seasons (Herbst et al. 2000). BN, by contrast, is a B3-B4 star with a mass $\sim 6-8M_\odot$ (and a maximum mass of 20 $M_\odot$ if the B0 spectral type inferred from HII region characteristics is adopted). It is the most massive periodic variable detected thus far in the Orion region. The next brightest stars having significant periods in Carpenter et al. are >2.2 mag fainter at K_s with spectral types K0 and later.

BN's periodic variability could be due to a number of well-recognized phenomena, although none of the following explanations seems totally satisfactory.

Periodic variability in young stars is usually interpreted in terms of long-lived nonuniformities in photospheric structure, i.e. spots that are either cooler or hotter the stellar effective temperature. These spots rotate with the star and modulate the lightcurve as they pass through the line of sight of the observer. Interpreted as stellar rotation, the 8.28 day period implies an equatorial velocity of $\sim$30 kms^{-1} which is on the slow tail for rotation of intermediate- and high-mass young stars in the ONC (Wolff, Strom, & Hillenbrand 2001). It is not generally accepted that massive stars like BN have the surface magnetic structures required for production of cool spots. However, given that BN is a protostar, accretion may produce surface shocks perhaps also requiring magnetic fields in the form of ordered magnetic dipoles which lead to hot spots as material from the circumstellar environment falls in along them.

Considered independently, the variability amplitudes at H and K_s can be well-modelled by spots with ΔT$\approx$15,000 K from the photosphere and $\sim$15-20% coverage, or ΔT$\approx$5,000 K and $\sim$50% coverage, as examples. However, neither cool nor hot spots are capable of producing the small H-K_s color amplitude since the effect of adding a spot is essentially colorless in the near-infrared given the early B photosphere (<0.02 mag for ΔT<20,000 K and coverage <50%). If spot-modulated rotation is the cause of the observed photometric periodicity, the phase and the amplitude both should change on timescales of months to years as the spot structure varies. Although the 2000 February data point phases well with the period derived for the 2000 March/April time series, the 1998 March data point does not; however, this could be due simply to accumulation of period error over the longer time baseline.

Pulsating behavior leads to short periods (0.1-0.3 day) in radial modes and to only slightly longer periods (<1 day) in nonradial modes (e.g. βCep stars in the early B range and 53 Per type stars and others at late B types). Both the amplitude and the near-sinusoidal shape of BN's lightcurve are consistent with certain types of pulsational behavior, but the period is too long. Longer period variability ($\sim$2-30 days) in massive stars is often explained in terms of winds, with some mechanisms requiring binary systems. The radio spectral index of BN is $\alpha = 0.8\pm0.2$ from 2-6 cm (Felli et al. 1993), consistent with thermal emission from an ionized stellar wind.

The observed period and mass estimate for BN imply an orbital radius of $\sim$0.15 AU for any hypothetical low-mass companion. If an outflow/wind from a companion was colliding with the outflow/wind from BN, pulsating behavior within the interaction region might be identified via x-rays (e.g. Ishibashi et al. 2000 for Eta Car). BN was seen in heavily absorbed x-rays by Chandra (Garmire et al. 2000). However, the Chandra position was 1.1" northwest ($\sim$500 AU) of the near-infrared position, whereas all other x-ray/optical-infrared matches were within 0.5". Garmire et al. attribute the offset, if real, to physics associated with outflow phenomena interacting with stationary, dense cloud material; no binary system is required.

Another scenario to consider is an eclipsing binary. BN's lightcurve does not seem consistent with a fully eclipsing system given its low amplitude and nearly sinusoidal nature. A partial eclipse situation with a near-equal mass/size companion, a small orbital separation ($\sim$10 R_*), and a reasonable inclination ($\sim 40°$) would match the gross shape, period, and amplitude of the phased lightcurves. In the near-equal mass situation, the true orbital period would be double that derived naively from observations since a single revolution produces two minima and two maxima. However, eclipses should exhibit the same amplitude in all bands (modulo limb darkening), which is not what is observed for BN unless the companion has the same radius but the colors of a much cooler star. Interestingly, Scoville et al. (1983) and others have suggested the possibility of wide binarity for BN to explain its large radial velocity relative to other ONC stars and to the ambient cloud.

A further possibility is periodic occultation by asymmetry in a circumstellar disk at the 0.15 AU orbital radius implied by the period. High column density, partially grey, orbiting material could produce the shape of the lightcurve as well as the color and magnitude amplitudes. It is interesting in this context to note that Biscaya et al. (1997) claimed time variability in BN's 2μm CO bandhead emission lines, and that no emission is present in the spectrum of Penston et al. (1971). The CO lines are formed in the dense, hot circumstellar environment and their time variability may have the same physical origin as the continuum variability found by us.

Finally, we note that there may be historical precedent for photometric variability in BN, as detailed in Table 2. One must be cautious in interpreting this ensemble of early near-infrared measurements as indicative of large scale flux variations, however. The observational complexities of working in the Orion region combined with a variety of aperture sizes may explain entirely the apparent differences in photometry.

5. SUMMARY

We have found photometric modulation in H- and K_s-band lightcurves for BN consistent with periodic behavior. During 2000 March/April the period was 8.28 days with a Lomb-Scargle false alarm probability of <0.1%. The amplitude of the nearly-sinusoidal lightcurve was $\sim$0.2 mag peak-to-peak ($\sim$0.05 mag root-mean-squared). The origin of the periodicity is not immediately obvious. Modulation of the lightcurve due to rotation of inhomogeneities in either the photosphere or the inner circumstellar dust distribution is the least complicated model. Further multiwavelength photometric as well as emission-line profile monitoring can probe period persistence, phase stability, and physical origins for the periodic behavior.

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TABLE 1

TIME SERIES PHOTOMETRY FOR THE BN OBJECT

Julian Date	H [mag]	K_s [mag]	err(H) [mag]	err(K_s) [mag]
2450891.509	8.949	5.087	0.028	0.004
2451580.546	8.865	5.094	0.018	0.011
2451607.526	8.892	5.121	0.023	0.014
2451608.520	8.934	5.111	0.027	0.010
2451609.520	8.936	5.081	0.026	0.012
2451610.519	8.819	5.017	0.017	0.003
2451612.553	8.813	5.003	0.027	0.021
2451614.516	8.855	5.017	0.019	0.010
2451615.515	8.904	5.079	0.022	0.012
2451616.514	8.949	5.103	0.017	0.012
2451617.514	8.943	5.098	0.017	0.013
2451618.513	8.869	5.040	0.020	0.021
2451619.511	8.837	4.998	0.021	0.025
2451621.510	8.768	4.996	0.017	0.009
2451622.512	8.818	5.008	0.026	0.014
2451623.509	8.872	5.039	0.014	0.020
2451624.507	8.886	5.082	0.022	0.010
2451625.507	8.904	5.084	0.021	0.013
2451626.506	8.891	5.051	0.019	0.014
2451627.505	8.811	5.015	0.010	0.017
2451628.499	8.757	4.967	0.020	0.018
2451629.498	8.778	4.956	0.032	0.016
2451630.498	8.778	4.990	0.017	0.009
2451631.497	8.842	5.062	0.022	0.011
2451633.491	8.947	5.125	0.022	0.009
2451634.490	8.886	5.060	0.022	0.011
2451635.489	8.850	5.002	0.009	0.007
2451639.485	8.819	4.996	0.017	0.007
2451640.480	8.906	5.110	0.020	0.015
2451641.479	8.947	5.114	0.009	0.013

TABLE 2
HISTORICAL PHOTOMETRY FOR THE BN OBJECT

Reference	Observation Date [UT]	Aperture Size [arcsec]	H [mag]	K [mag]	err(H) [mag]	err(K) [mag]
Becklin & Neugebauer (1967)	1965, January	13	9.8	5.2	?	?
Neugebauer (2000)	1968, September 15	?	9.19	4.88	0.10	0.07
Low et al. (1970)	?	?	9.60	4.87	?	?
Neugebauer (2000)	1969, December 8	?	8.57	4.72	0.15	0.15
Penston (1973)	1971, March 9	15	8.48	4.5	0.13	?
Neugebauer (2000)	1974, September 21	7	9.45	4.76	0.10	0.10
Lonsdale et al. (1982)	1980, February	3.5	9.2	5.1	<0.3	<0.3
Neugebauer (2000)	1981, March 14	6	9.39	4.93	0.06	0.04
Hyland et al. (1984)	1982 or 1983	4	–	5.5	–	<0.01
Minchin et al. (1991)	1988, January	6	9.8	5.4	0.1	0.1
This Paper	1998, March 19	8	8.95	5.09	0.03	<0.01
Hillenbrand & Carpenter (2000)	1999, February 9	1.8	9.36	–	<0.01	–
This Paper, mean over time series	2000, March/April	8	8.87	5.04	<0.03	<0.02