Outbursting Young Stellar Object PGIR 20dci in the Perseus Arm

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ABSTRACT

We report the discovery of a likely outbursting Class I young stellar object, associated with the star-forming region NGC 281-W (distance \(\sim 2.8 \) kpc). The source is currently seen only at infrared wavelengths, appearing in both the Palomar Gattini InfraRed (1.2 \(\mu\)m) and the Near Earth Object Widefield Infrared Survey Explorer (3.4 and 4.6 \(\mu\)m) photometric time-domain surveys. Recent near-infrared imaging reveals a new, extended scattered light nebula. Recent near-infrared spectroscopy confirms the similarity of PGIR 20dci to FU Ori type sources, based on strong molecular absorption in CO, \(H_2O\), and OH, weak absorption in several atomic lines, and a warm wind/outflow as indicated by a P Cygni profile in the He I 10830 \(\AA\) line. This is a rare case of an FU Ori star with a well-measured long term photometric rise before a sharper outburst, and the second instance of an FU Ori star with a documented two-step brightening in the mid-infrared.

1. INTRODUCTION

Episodic accretion in young stellar objects is an important aspect of mass accumulation in stars. It also plays a determining role in the evolution of circumstellar disks, and likely influences the process of planet formation, as well as planetary survival. Armitage (2015) provides a review of disk physics in young stars, including nonsteady accretion and disk instabilities.

In “classical” T Tauri type young stars, the accretion process is controlled mainly by physics in the inner disk and magnetospheric region that connects the disk to the star. Observed time-variability in broad-band photometry and in emission line profiles of these sources is dominated by stochastic behavior, with timescales from hours to days (e.g. Findeisen et al. 2015; Cody &
The empirical zoo of accretion-related photometric behavior has been measured in unprecedented detail for young stars by CoRoT, Spitzer, Kepler, and now TESS, all of which sample timescales from minutes to a few months. Ground-based surveys such as ASAS, PTF, ZTF, and ATLAS in the optical, and VVV in the infrared, by contrast, typically have lower precision and cadence (day to a few days), but the advantage of long duration monitoring. Gaia and WISE+NEOWISE also provide precise space-based photometric data, but at much lower cadence (months), with total duration exceeding a decade now. Many of these surveys have all-hemisphere or even all-sky coverage, enabling rare event detection – including episodic accretion outbursts in very young stars.

Accretion-driven outbursts associated with young stellar objects have been identified at an increasing rate over the past decade. The discoveries have come from both the ground-based and the spaced-based platforms. Infrared surveys have the advantage of being able to penetrate the high levels of extinction towards the molecular clouds where young stars are born, and to some extent the additional circumstellar extinction of the youngest self-embedded sources. Outbursts are most commonly events labelled as EX Lup outbursts (also known as EXors) which are a few magnitudes in amplitude, and last a few months to one-to-two years. The more extreme and rarer cousins are labelled FU Ori outbursts (also known as FUors), which can be up to 5-6 mag in amplitude and last decades to centuries. An increasing number of objects are unable to be cast neatly into either of these categories, however.

Our knowledge of the typical amplitudes, durations, and duty cycles for young star outbursts is still in its infancy. In particular, the large-scale FU Ori outburst events are intrinisically rare, and those few that have been captured in-progress have not been particular well-characterized\(^1\). The most recent FU Ori outburst discoveries are Gaia 17bpi (Hillenbrand et al. 2018), Gaia 18dvy (Szegedi-Elek et al. 2020), and NWISE-F J213723.5+665145 (Stecklum 2020; Connelley & Reipurth 2020). The total census of FU Ori type stars numbers < 30 objects at present, with less than half of these having had their outburst actually observed (rather than inferred from imaging at well-separated pre-outburst and post-outburst epochs).

We report here on the discovery of substantial photometric brightening of an object designated as PGIR 20dci. This source is located at R.A. = 00:52:20.21, Dec. = +56:34:03.9, and we associate it with the NGC 281-W star forming region. The object appears to be a bona fide FU Ori star that has just reached a plateau phase in its brightening.

2. SOURCE ENVIRONMENT

NGC 281, also known as Sh 2-184, is an H II region located in the Perseus spiral arm. While the traditional distance in the literature on the stellar population is \(~2.2\) kpc, astrometry from Gaia DR2 (Gaia Collaboration et al. 2018) indicates a somewhat further \(2.8\) kpc. This is also the distance derived by Sato et al. (2008) from parallax studies at radio wavelengths of a maser population associated with NGC 281-W (where PGIR 20dci is located). These results place the region on the far side of the Perseus arm, and about 300 pc out of the Galactic plane.

IC 1590 (<2 Myr) is the main stellar cluster within the nebular region, and contains the bright ionizing sources collectively designated as HD 5005. This source is now a spatially resolved multiple

\(^1\) The situation can be compared to shorter timescale rare occurrences such as tidal disruption events and nearby supernovae, which garner armies of dedicated followers.
star system, consisting of components with spectral types O6.5, O8, and O9 (Guetter & Turner 1997). The cluster thus draws analogies in the literature as a Trapezium type system. The stellar population of the IC 1590 cluster was investigated by Guetter & Turner (1997) and by Sharma et al. (2012), the latter of whom find a size $r \approx 6.5$ pc.

To the southwest of the main cluster IC 1590, is a dark lane known as NGC 281-W. Another dark area just to the east of the nebulosity is designated NGC 281-E. These are the locations of molecular clouds at the same distance as the large nebula, and presumably situated, at least in part, on its near side. APOD provides an optical picture\(^2\) that may clarify the geometry for some readers. CO maps of the overall region can be found in Elmegreen & Lada (1978) and Lee & Jung (2003), who provide evidence for cloud compression coming from the direction of the cluster and H II region.

The NGC 281-W molecular core has a bright sub-millimeter and far-infrared source, readily apparent in Herschel/SPIRE (Griffin et al. 2010) and SCUBA-2 (Holland et al. 2006) maps. This dust clump harbors a collection of mid-infrared point sources to its east and southeast, as seen in WISE (Wright et al. 2010) images.

The portion of this highly embedded cluster that is visible in the near-infrared was discovered and studied by Carpenter et al. (1993). These authors targeted the region with early near-infrared imaging capabilities based on the position of IRAS 00494+5617. They found a cluster size $r = 0.7$ pc (corrected here for differences in the distance assumption), with northeastern and southwestern portions separated by a ridge of high extinction. The “typical” extinction towards the embedded sources was estimated at $A_V \approx 10$ mag, with peak $A_V \approx 45$ mag. Carpenter et al. (1993) also derived a mass of $210 M_\odot$ for the associated CS core\(^3\). The same area of NGC 281-W was specifically targeted in a similar study by Megeath & Wilson (1997) using more sensitive radio and infrared observations.

The object of interest here, PGIR 20dci, is located within the region of these previous surveys, about 30'' west of the embedded cluster center. Figure 1 shows a portion of the field imaged by Megeath & Wilson (1997), with the position of PGIR 20dci designated. Although faintly visible at $K'$-band in this archival image, PGIR 20dci has not been previously cataloged, studied, or characterized.

3. OUTBURST DISCOVERY AND VALIDATION

In this section, we describe the initial photometric alert that drew our attention to PGIR 20dci. We then detail the optical, near-infrared, and mid-infrared photometric forensics work leading to establishment of the outburst profile over time.

3.1. Gattini 1.2 µm (J-band) Lightcurve

The Palomar Gattini InfraRed survey (PGIR; De et al. 2020a; Moore & Kasliwal 2019), observes the sky every two nights in the near-infrared J-band, to a median depth of $J = 15.7$ mag (AB). The faint limit is much brighter than this in crowded or confused regions, such as near the Galactic plane and in high surface brightness regions, such as NGC 281-W.

On 2019, August 31, a “hostless” source was first detected in PGIR as a positive image subtraction, and flagged (by co-author KD) for photometric and spectroscopic follow-up. The initial source position required some refinement due to the 8'' pixel size of PGIR. There are no counterparts in optical (e.g. PanSTARRS Flewelling et al. 2016) or near-infrared (2MASS Skrutskie et al. 2006)

\(^2\) https://apod.nasa.gov/apod/ap110825.html

\(^3\) A mass in CO of $2500 M_\odot$ was also reported by Carpenter et al. (1993), though the NGC 281-W cloud is somewhat larger than the area studied, with Lee & Jung (2003) finding a total mass for the extended cloud of $1 - 3 \times 10^4 M_\odot$.  


survey catalogs, though a hard stretch of the 2MASS images does reveal a faint detection at $K_s$ and perhaps $H$. A nearby WISE catalog (Cutri et al. 2013) source at 00:52:20.41 +56:34:03.3 was determined to be the source that had brightened. The brightening is also recorded in NEOWISE (Mainzer et al. 2014) data. The consequent increase in signal-to-noise likely yields better astrometry, and hence a more accurate true source position of 00:52:20.21 +56:34:03.9, which we adopt. This position is 1.3″ away from the position reported for the fainter WISE source, and 4-5″ from the PGIR position.

Figure 2 shows the lightcurve produced from the PGIR forced difference photometry pipeline. PSF-fit photometry is performed, with noise uncertainty at the location of the transient estimated, as described in De et al. 2020b, from difference images produced using the ZOGY algorithm (Zackay et al. 2016).

Since its discovery at $J = 14.97$ mag, PGIR 20dci has slowly increased in brightness. The brightening trend observed during the 2019-2020 season (Figure 2) can be fit with a linear slope of $-0.116 \pm 0.011$ mag/month. During the latter part of 2020 the lightcurve appears to have plateaued, and a linear fit is consistent with zero slope.

3.2. Pre-Discovery Photometric Information

In this section, we discuss the limited photometric record available for PGIR 20dci.
Figure 2. Top panels: Discovery imaging sequence showing a $4' \times 4'$ region centered on PGIR 20dci; orientation is the standard north upward and east to the left. From left to right are: the PGIR image from 2019-10-31 (MJD = 58787), the static reference image of the field created from a series of earlier images taken between 2018-10-28 and 2019-01-29, and the subtracted difference image. PGIR 20dci is clearly visible in the last panel, and is marked in all three. Bottom panel: $J$-band lightcurve of PGIR 20dci during 2019 and 2020. The observed upward slope in the data points at MJD < 59000 corresponds to a source brightening rate of $-0.116 \pm 0.011$ mag/month. The lightcurve then flattens, and a fit for MJD > 59000 is consistent with zero slope ($-0.017 \pm 0.022$ mag/month). We note that $J$-band observations from much earlier indicate a significantly fainter source, with estimated limits $J > 17.1$ mag (2MASS) and $J > 20$ mag (Megeath & Wilson 1997); see text.

3.2.1. Optical and Near-Infrared

At the time of its PGIR detection, PGIR 20dci was invisible in optical time-domain survey data, including ASAS and ZTF. Recently, however, a faint optical source with $r = 20 - 20.5$ mag is transiently present in ZTF alerts (Masci et al. 2019). There is not a useful optical lightcurve, however, due to infrequent detection and large error bars.

We also note that PGIR 20dci was undetected in earlier, deeper, imaging of the NGC 281-W region with HST in the optical. This includes in its longest wavelength filters as provided via the HLA-R and HLA-I composite images of the Hubble Legacy Archive. PGIR 20dci is also undetected in archival Keck/DEIMOS images of the region from 2010, October 6.

In the near-infrared, PGIR 20dci was undetected by 2MASS (Cutri et al. 2003), as noted above. While the nominal 2MASS survey limit is $J < 15.8$, we derive a more accurate number for this exact environment by considering the error vs magnitude distribution of sources within $4'$ of PGIR 20dci. We find that $10\sigma$ photometry is available to $J = 16.1$ mag and $5\sigma$ photometry to $J = 17.1$
While the diffuse background is high in the NGC 281-W region, the dark cloud renders the point source background and confusion lower than would be the case otherwise. Thus, the 2MASS magnitude limit is plausibly deeper than nominal. We conclude that a reasonable flux upper limit for PGIR 20dci at epoch 2000, January 13 is approximately $J > 17.1$ mag.

In the deeper $J$-band imaging of Megeath & Wilson (1997), PGIR 20dci is also not apparent, except for perhaps a faint low surface brightness smudge near the edge of detection. The claimed faint point source limit of these data is $J \approx 21$ mag. PGIR 20dci does, however, have an apparent faint counterpart in the $K'$-band imaging of Megeath & Wilson (1997), as indicated in Figure 1. Although the sources from this study are not cataloged, the authors report that the fainter stars in the displayed image have $K' \approx 18.5$ mag (80% completeness level). PGIR 20dci thus appears to have experienced a $\sim 5$ mag brightening since the mid-1990's epoch of the Megeath & Wilson (1997) data acquisition.

### 3.2.2. Mid-Infrared Spitzer

In the mid-infrared, there is also a faint counterpart to PGIR 20dci in Spitzer/IRAC (Werner et al. 2004; Fazio et al. 2004) imaging. The source appears blue in comparison to the main embedded cluster, approximately 30' to the east of PGIR 20dci, perhaps due to somewhat lower extinction away from the center of the molecular core (see contours in Figure 1).

There are three relevant Spitzer/IRAC AORs, one for P.I. Fazio in 2004 (AORKEY 4127744) and two for P.I. Wolk in 2009 (AORKEYs 34780160 and 34780416). The former, from Spitzer’s cryogenic phase, includes all four IRAC bands (3.6, 4.5, 5.8, and 8 μm). The latter two were taken in the post-cryo phase of Spitzer and thus include only IRAC1 (3.6 μm) and IRAC2 (4.5 μm). We performed aperture photometry at the target’s location in the pipeline-produced post-BCD mosaics using a radial aperture of 3 native pixels (1.2"/pixel) and a background annulus from 3-7 native pixels. Aperture corrections were applied as appropriate to the cryo and the post-cryo observations, as described in the IRAC Instrument Handbook. The Instrument Handbook also has the zero points we used for converting the flux densities to magnitudes. Our photometric results for Spitzer/IRAC are provided in the first three rows of Table 1.

From some of these same Spitzer data, Sharma et al. (2012) found [S3.6] or IRAC1 = 14.40 mag and [S4.5] or IRAC2 = 12.89 mag using a similar 3.6" radial aperture to us, but a smaller 3.6"–8." sky annulus. These values are consistent with our results for the first observation epoch, in 2004. We also note that IRSA’s SEIP catalog contains a source SSTSL2 J005220.20+563403.8 with IRAC1 = 14.57 mag and IRAC2 = 12.80 mag, adopting the 3.8" aperture values and applying the flux-to-magnitude conversions above, again consistent with our measurements for the 2004 epoch, within the reported errors.

Finally, we note that there are also Spitzer/MIPS observations of the region available in the 24 μm band. These MIPS1 data were taken in 2006, February, which is between the two Spitzer/IRAC epochs. It would be valuable to be able to compare the 2006 MIPS1 photometry to the 2010 W4 photometry, for reasons that will become apparent below. Unfortunately, however, the MIPS1 imaging results in only flux upper limits for PGIR 20dci.

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4 [https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook](https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook). Specifically, we used values of 1.124, 1.127, 1.143, & 1.234 for the 4 channels in the cryogenic era, respectively, and 1.125 & 1.120 for the 2 channels in the post-cryo era, respectively.

5 280.9, 179.7, 115.0, & 64.13 Jy for the four IRAC channels, respectively.

6 [http://irsa.ipac.caltech.edu/data/SPITZER/Enhanced/SEIP/overview.html](http://irsa.ipac.caltech.edu/data/SPITZER/Enhanced/SEIP/overview.html)
Table 1. Spitzer, WISE, and NEOWISE Photometry a for PGIR 20dci

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<th>IRAC1 3.6 (\mu m)</th>
<th>IRAC2 4.5 (\mu m)</th>
<th>WISE2 4.6 (\mu m)</th>
<th>IRAC3 5.8 (\mu m)</th>
<th>IRAC4 8.0 (\mu m)</th>
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aIRAC columns contain Spitzer/IRAC photometry derived here, with transformations made to the WISE photometric system appearing in the WISE columns as parenthetical entries. WISE columns contain photometry from several sources. The first WISE entry is taken directly from the IRSA AllWISE catalog. Subsequent entries are derived here from observations reported in the IRSA MEP and NEOWISE-R catalogs, combining individual measurements by “visit”; see text.

3.2.3. Mid-Infrared AllWISE

WISE images at the comparable bands WISE1 or W1 (3.4 \(\mu m\)) and WISE2 or W2 (4.6 \(\mu m\)) have lower spatial resolution, but do show a source that appears more distinct and pointlike in the unWISE image processing (Lang 2014). The AllWISE catalog (Cutri et al. 2012) records a source WISEA J005220.41+563403.3 with reported photometry given in Table 1. We took the AllWISE profile fitting magnitudes and errors, as quoted. The measurements are rated as “AAAA” in photometric quality, meaning SNR > 10 in each of the four bands, and they are unsaturated.

3.2.4. Mid-Infrared Colors

The available colors of the PGIR 20dci progenitor are \(IRAC1 − IRAC2 = 1.60\) and \(IRAC2 − IRAC3 = 1.09\) mag from Spitzer, and \(W1 − W2 = 1.12\), \(W2 − W3 = 5.82\), and \(W3 − W4 = 2.76\) mag from AllWISE.

These colors place the object firmly within the Class I category of young stellar objects, meaning a steeply rising spectral energy distribution that is best explained by the presence of a massive circumstellar envelope. The colors are too red to be consistent with a geometrically flatter disk, as is characteristic of Class II sources. PGIR 20dci is, however, even redder than most Class I sources, which indicates substantial foreground extinction.

3.3. Mid-Infrared WISE+NEOWISE Lightcurve
Figure 3. Top panels: Spitzer 2009 and WISE 2010 images of a $103'' \times 93''$ field centered on PGIR 20dc1; orientation is the standard north upward and east to the left. As described in the text, Spitzer photometry was derived using an aperture radius of $3.6''$ (marked circle) while WISE photometry comes from the profile fitting measurements. Although the WISE image is dominated by brighter sources, there are no confusion flags set in any of the WISE or NEOWISE catalog data for the profile fitting. Bottom panel: Mid-infrared lightcurve assembled from available Spitzer, WISE, and NEOWISE data. Error bars are indicated, though in some cases are smaller than the data points. The Spitzer photometry is plotted both as observed (open squares) and color corrected into the WISE photometric system (filled squares); see text. The recent photometric brightening that was detected based on PGIR data is clearly measured by NEOWISE as well. A previous significant brightening occurred between the Spitzer 2009 and WISE 2010 observations. Each of the two large jumps is preceded by a shallow rise phase. Vertical blue line indicates the epoch of the infrared spectrum shown in Figure 6.

We collected additional mid-infrared photometry from the WISE Multi-Epoch and NEOWISE (Cutri et al. 2015) mission archives via IRSA\textsuperscript{7}, rejecting measurements with qi\_fact=0 or qual\_frame=0. For the WISE Multi-Epoch catalog and the subsequent, ongoing NEOWISE monitoring data, we took the median of all profile fitting magnitude measurements within each spacecraft “visit” covering the position, and we calculated the error as the dispersion among these magnitudes. The median time span per WISE or NEOWISE visit is about 1.25 days. Results are provided in Table 1.

\textsuperscript{7} https://irsa.ipac.caltech.edu/Missions/wise.html
As illustrated in Figure 3, the mid-infrared lightcurve of PGIR 20dci experienced an exponential rise phase over the past few years, that appears to be plateauing during 2020. Considering only the three NEOWISE measurements at MJD = 58491.8, 58698.2, and 58858.1, before the plateau, the rise rate was $-0.121 \pm 0.015$ mag/month or $-1.40$ mag/year during 2019-2020. We note that this is identical, within the errors, to the slope derived for the $J$-band lightcurve ($-0.116 \pm 0.011$ mag/month; see discussion above regarding Figure 2). Before this steep recent rise, there was a much shallower but steady upward trend in the WISE/NEOWISE lightcurve between 2010 and 2019, with a rise slope of only $-0.01$ mag/month or $-0.13$ mag/year.

As discussed above, prior to the 2010 WISE mission measurements, there are data available in 2009 and 2004 from Spitzer. A shallow rise is also seen in these data, though there are a limited number of data points. The steeper jump that is implied between the Spitzer and WISE epochs occurs in a fairly narrowly confined time frame, within 2009 September 6 (Spitzer) and 2010 January 26 (WISE), and warrants critical investigation.

The two shortest wavelength Spitzer and WISE filters are similar, and Jarrett et al. (2011) find agreement in large-scale photometry comparisons to within 2-3%. However, PGIR 20dci is an extremely red source, beyond the range of colors available to Jarrett et al. (2011), and thus we need to consider potential color terms between the earlier Spitzer and later WISE photometry. Similar considerations were also made for the lightcurve analysis of Gaia 17bpi (Hillenbrand et al. 2018) and PTF 14jg (Hillenbrand et al. 2019), where color transformations were derived and implemented, but not magnitude transformations. Here for PGIR 20dci, we have tried to assess more carefully the impact of color terms on the lightcurve, by looking at a large sample of young stellar objects observed with both Spitzer and WISE. While there is a narrow correlation in the magnitudes themselves, when considering the IRAC1–W1 and IRAC2–W2 transformations as a function of IRAC1-IRAC2 color, the comparison data show a fanning out towards redder IRAC1-IRAC2 color, which introduces significant uncertainty. Identical issues were investigated by Antoniucci et al. (2014, see their section 2.1.1) and we have adopted their corrections.

For the IRAC1-IRAC2 color of PGIR 20dci, this amounts to shifts of approximately 0.5 mag fainter in going from IRAC1 to W1, and -0.25 mag brighter in going from IRAC2 to W2. Figure 3 illustrates both the observed and the WISE-corrected Spitzer magnitudes, which also appear in the WISE columns of Table 1.

In order to negate the conclusion of a large jump in brightness between the last Spitzer epoch and the first WISE epoch, the color corrections to the photometry would have to be much larger than currently supposed (which is certainly possible), but also in the opposite direction for the Spitzer IRAC1 channel. We also note that, even among the very red sources in this spatial region, PGIR 20dci is an outlier in direct comparisons of Spitzer vs AllWISE photometry.

We have also checked the WISE/NEOWISE photometry flags, finding no entries in the $w[12]/cc$ _map_str_ (contamination and confusion) column, and only non-event entries in the $na$ (deblending) column. The $nb$ (multiple PSF) column indicates that a single profile is used in > 80% of the measurements; only < 20% of the measurements (all towards the fainter end) require a second PSF, perhaps to account for the faint star just to the north of PGIR 20dci (see the Spitzer image panel in Figure 3). The $w[12]/flg_1$ (5.5" aperture confusion) column, on the other hand, indicates

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8 $(W1 - W2)_{corr} = 1.62 \times (IRAC1 - IRAC2) - 0.04$ mag, with rms = 0.24 mag.

9 $W1_{corr} = IRAC1 - 0.27489 \times (IRAC2 - IRAC1) + 0.07146$ and $W2_{corr} = IRAC2 + 0.1422 \times (IRAC2 - IRAC1) - 0.01855$

10 https://wise2.ipac.caltech.edu/docs/release/neowise/expsup/sec2_1a.html
that about 8% of the aperture photometry measurements have some identified source of confusion; this is not significant for the w1mpro magnitude measurements that we have adopted, however. The WISE/NEOWISE aperture photometry exhibits the expected trends with aperture size, with the 5′′.5 aperture undersized and producing magnitude overestimates, and other apertures oversized and thus having magnitudes that well-underestimate the profile fitting magnitudes.

Even if the undersized 5′′.5 aperture photometry were used, the brightness jump between the Spitzer 2009 and WISE 2010 measurements would remain, albeit reduced by about 0.25 and 0.75 mag in W1 and W2, respectively. Overall, the profile fitting photometry we have adopted is more robust to bad pixels, cosmic rays, and the need to establish aperture corrections.

Finally, we can consider the evidence for color changes as the source has brightened in the mid-infrared. The recent brightening of PGIR 20dci has been colorless, within the errors. The median color over the 2014-2019 NEOWISE epochs is consistent with a constant value of \( W1 - W2 = 1.40 \) mag and rms = 0.21 mag, and there is no deviation from this constant color baseline in the latest, much brighter NEOWISE measurement. In 2010, however, the measured WISE colors are \( W1 - W2 \approx 1.23 \) mag, for each of the three epochs, so marginally bluer in the period just after the 2009-2010 jump in brightness. The 2009 and 2004 Spitzer colors are both IRAC1-IRAC2 \( \approx 1.60 \), which after applying the Spitzer-to-WISE color transformation quoted above, results in a corresponding \( W1 - W2 = 2.55 \) mag. Applying the Antoniucci et al. (2014) magnitude corrections detailed above results in fairly similar colors of 2.40, 2.31, and 2.26 mag for the the three Spitzer epochs. This suggests that the color of PGIR 20dci became bluer by about 1 mag in \( W1 - W2 \) as it brightened during late 2009 and very early 2010 period, before reddening by a small amount (\( \approx 0.2 \) mag) during its subsequent evolution.

In summary, the mid-infrared lightcurve of PGIR 20dci shows that the source has undergone a long-timescale, two-step rise from a faint state to a bright state over the past \( \sim 15 \) years. During the period 2004-2019, the source increased its mid-infrared brightness by \( > 3.5 \) mag in total. There was a shallow brightening from 2004-2009, a significant jump in brightness during a 4 month time frame in late 2009 or early 2010, a second shallow rise phase, and finally a more recent brightness jump beginning in 2019.

4. FOLLOW-UP OBSERVATIONS AND DATA ANALYSIS

In this section, we describe the imaging and spectroscopy that we collected on PGIR 20dci.

4.1. Imaging

4.1.1. Data Acquisition

PGIR 20dci was flagged for follow-up with SEDM (Spectral Energy Distribution Machine; Blagorodnova et al. 2018) in its imaging mode. A sequence in the gri filters was acquired on 2020 August 14 (UT) and reduced using the photometric reduction pipeline.

On 2020 August 28, we obtained near-infrared imaging of PGIR 20dci using the Wide Field Infrared Camera (WIRC; Wilson et al. 2003) on the Palomar 200-inch telescope. The data were acquired as a series of dithered exposures in J, H, and Ks bands for a total exposure time of 495, 330, and 300 seconds, respectively. The data were reduced, stacked and photometrically calibrated using the pipeline described in De et al. (2020a).

4.1.2. Findings
No counterpart to PGIR 20dci was detected in $g$ and $r$ bands, with an approximate upper limit of $>21$ mag. However, we detect a faint extended source in $i$ band, coincident with the bright nebula detected in the near-infrared image. The final $Ks$-band image was shown in Figure 1. A close-up on PGIR 20dci appears in Figure 4, which highlights the extended cometary structure of the source in the near-infrared. Figure 5 shows the JHK color composite image.

Taken together, the optical and infrared imaging suggests an extremely red source, as well as a bright, extended, scattered light component associated with the brightening of PGIR 20dci. The angular size of the extended structure corresponds to a physical size $\sim$14,000 AU.

In order to encompass the non-point source, extended nature of PGIR 20dci, we measured photometry from the Palomar/WIRC images using a fairly large aperture radius of 9 pixels ($2''.25$), whereas a 5-pixel ($1''.25$) radius would suffice for point sources. Using the smaller radius would decrease the brightness of PGIR 20dci by about 0.1 mag. We calibrated by matching to 110 sources in common between our final images and the 2MASS catalog. We find $J = 14.83$, $H = 13.08$, and $Ks = 11.77$ mag in 2020, September. The near-infrared colors of PGIR 20dci in outburst are thus $J - H = 1.75$ mag and $H - Ks = 1.31$ mag. This location in a $J - H$ vs $H - K$ diagram is consistent with that of a young stellar object that is highly reddened.

4.2. Spectroscopy
4.2.1. Data Acquisition
On 2020 August 13, PGIR 20dci was observed with Keck II and NIRES (Near Infrared Echellette Spectrometer), which is part of the family of similar instruments described in Wilson et al. (2004). The detector records a prism-dispersed simultaneous $YJHK$ spectrum at resolution $R \approx 2700$. Four spectra were acquired using a 6$''$ ABBA nodding pattern, with integration time of 90 seconds at each position. The data were reduced using a modified version of spextool (Cushing et al. 2004), and flux-calibrated with the telluric A0V standard star HIP 6002 using the xtellcor code (Vacca et al. 2003). Figure 6 shows the final extracted and combined spectrum. Due to the very red nature of the source, there is little signal at the shorter wavelengths, and thus we show only the $JHK$ spectral region.

On 2020 September 4, a second spectrum was obtained at $R \approx 2700$ with the Palomar 200” and the TripleSpec (Herter et al. 2008) near-infrared spectograph. Although lower signal-to-noise, and not shown as a result, the spectrum is broadly the same in its shape and presence of strong spectral features as the Keck/NIRES spectrum from a month earlier. However, the flux level is brighter. Considering Figure 2, the flux at this point in time could have been several tenths of a magnitude brighter, though the error on this estimate is large. A more likely explanation is that the TripleSpec slit (1.0") is wider than the NIRES slit (0.55"), and thus the spectrum would include more of the bright extended structure of the source (see Figure 4). Normalizing the two at $K$-band, the $K$-band slope is identical to that shown in Figure 6, but there is a sharper break just before the $CO$ region, resulting in even deeper $CO$ absorption. The $H$-band region is then slightly brighter than the spectrum shown in Figure 6. This could mean that the source became slightly bluer while temporarily brighter at this epoch. However, we attribute the difference to the possibility that the two spectra may have included different parts of the extended nebula.
Figure 6. Comparison of PGIR 20dci (magenta) with the FU Ori stars V1057 Cyg (green, from Connelley & Reipurth 2018) and Gaia 17bpi (blue, from Hillenbrand et al. 2018). The spectral match is apparent in molecular $^{12}$CO, H$_2$O, and OH, and possibly weak TiO and VO. Also present are atomic lines of H I Pa$\beta$ (and possibly Br10), He I 10830 Å, and metals including Na I, Mg I, Al I, Si I, and Ca I. While the hydrogen and helium lines likely have some outflow aspect to their absorption, the metal lines originate in the photosphere, and combined with the molecular line absorption indicate a mixed temperature spectrum.
4.2.2. Findings

Focussing on the Keck/NIRES spectrum, PGIR 20dci is highly reddened, consistent with the extremely red mid-infrared colors measured by WISE. The comparison objects\textsuperscript{11} in Figure 6 are less reddened than PGIR 20dci. We can estimate the relative reddening, and thus the extinction, by applying a standard extinction law to find the the best spectral match to the V1057 spectrum. We find a differential extinction $\Delta A_V = 16$ mag, which can be added to a baseline $A_V = 4$ mag for V1057 (Connelley & Reipurth 2018). The total extinction towards PGIR 20dci is thus estimated to be $A_V \approx 20$ mag.

Spectroscopically, the most salient feature of PGIR 20dci is the strong $CO$ absorption. The source has both the $\Delta \nu = 2$ $CO$ bands in the $K$-band, and the $\Delta \nu = 3$ bands $CO$ in the $H$-band. There is also strong $H_2O$ in $J$-band and $H$-band, probably in $K$-band as well, and likely $OH$ in $H$-band. Less obvious is the expected $TiO$ and $VO$ absorption, though it may be weakly present. PGIR 20dci shares with Gaia 17bpi and V1057 Cyg in having clear $J$-band $H_2O$ absorption, and $H$-band and $K$-band $CO$ absorption. The $H_2O$ is weaker in PGIR 20dci, while the $CO$ is stronger. We note that the $CO$ in V1057 Cyg is atypically weak for FU Ori stars (Connelley & Reipurth 2018).

In terms of atomic lines, weak Na I, Mg I, Al I, Si I, and Ca I absorption are all present. There is also weak H I Pa$\beta$ absorption at 1.28 $\mu$m. The metal line strengths are similar to those seen in the comparison object Gaia 17bpi, and somewhat stronger than in V1057 Cyg. PGIR 20dci and Gaia 17bpi also have comparable Pa$\beta$, which is likely blueshifted and formed in a wind.

Notably, the He I 10830 Å line in PGIR 20dci shows a clear P Cygni profile (see inset panel within Figure 6). This is evidence of a strong wind or outflow, with blueshifted absorption in He I 10830 Å frequently seen in FU Ori stars (Connelley & Reipurth 2018).

In the nomenclature of Connelley & Reipurth (2018), PGIR 20dci appears to be a bona fide FU Ori star. In addition to having had its eruption observed, it satisfies all of the spectroscopic criteria: $CO$ absorption, $H_2O$ absorption, $VO$ or $TiO$ absorption (weakly), Pa$\beta$ absorption, lack of emission lines, weak metal absorption, and He I 10830 Å absorption. The hydrogen and helium lines likely have some outflow aspect to their absorption. The metal lines originate in the source photosphere, however, and combined with the molecular line absorption, indicate a mixed temperature spectrum.

5. DISCUSSION

The dramatic brightening behavior of PGIR 20dci is detected most obviously in the mid-infrared (Figure 3). The combined Spitzer, WISE, and NEOWISE data provide a long duration lightcurve. As the source has brightened, it has become detectable in the near-infrared as well (Figure 2). In the PGIR data, which is higher cadence, the brightness of PGIR 20dci is currently near the survey limit due to the high background in this field, and the lightcurve is thus somewhat noisy, though well-sampled. Over only the past few months, PGIR 20dci has appeared near the faint limit in the ZTF alert stream, sampling the red optical. Given that the PGIR data appears to indicate a current (second) plateau phase, the source may not become amenable to study in the optical.

A two-step rise is indicated by the mid-infrared lightcurve. PGIR 20dci first exhibited a blue rise of 1.8 mag in $W1$ and 0.8 mag $W2$, occurring between 2009 September 6 and 2010 January 26. This was followed by a shallower slope, long-term brightening over 2010-2018, which was colorless, amounting

\textsuperscript{11} Gaia 17bpi is a recent FU Ori outburst occurring in 2017 (Hillenbrand et al. 2018). V1057 Cyg is one of the originally defined FU Ori stars, estimated to have outburst in 1970 (Herbig 1977).
to only another 0.5 mag in both W1 and W2. The slope of the brightening increased during the latter part of 2018, and switched in 2019 to a much steeper rise rate. At this point, the source became detectable by PGIR in the near-infrared. PGIR and NEOWISE both record the lightcurve transition to a second plateau during 2020. The total brightening of PGIR 20dci over the past 16-25 years is \(\sim 5 - 5.5\) mag.

A similar two-step rise in the mid-infrared lightcurve was recorded for the confirmed FU Ori source Gaia 17bpi (Hillenbrand et al. 2018). However, the total duration of the first plateau phase in Gaia 17bpi was shorter, only 1-2 years, instead of the 5-10 years measured here for PGIR 20dci.

The most recent brightening phase of PGIR 20dci, since 2018, corresponds to about -0.12 mag/month in both the mid-infrared NEOWISE (W1 and W2) bands and the near-infrared PGIR (J) band. This compares well to the typical rise rates that can be derived for the optical lightcurves of historically documented FU Ori outbursts, which have a wide range, but are most frequently \(-0.05\) to \(-0.2\) mag/month (Hillenbrand, 2021, in preparation).

We can estimate a source luminosity near the outburst peak based on the brightness level of the apparent plateau in the lightcurve (\(J \approx 14.6\) mag from PGIR and \(r \approx 20.5\) mag from ZTF), and the adopted distance \(d = 2.81\) kpc. The bolometric correction is of course unknown, but adopting values appropriate for a mid-F type star leads to a luminosity estimate of 10-12 \(L_\odot\), with perhaps a factor of 3 uncertainty if the bolometric correction is \(\pm 1\) mag. This is on the far low side of FU Ori outburst peak luminosities. Only Gaia 17bpi, the only other source known to have exhibited a two-step mid-infrared brightening, like PGIR 20dci has, and HOPS 383, an embedded young star outburster whose status as an FU Ori type outburst is unclear, have luminosities this low.

The best studied FU Ori stars are the optically visible portion of the population, especially those bright enough for high dispersion spectroscopy. However, a sizable fraction of the known FU Ori stars, about 1/3, are seen only at infrared wavelengths due to high extinction (e.g. the \(A_V = 20 - 50\) mag population in Connelley & Reipurth 2018). Most of this group have been designated as FU Ori objects through source brightening at K-band that was noticed only post facto, rather than while it was actually happening. These embedded sources thus generally do not have quiescence-to-rise lightcurves available\(^\text{12}\) PGIR 20dci can be added to the list of optically invisible FU Ori candidates, but unlike the others, has had its photometric rise captured through wide-field continuous photometric monitoring programs.

6. SUMMARY

We have discovered an outbursting young stellar object within a known area of recent and ongoing dense star formation activity. PGIR 20dci is associated with the NGC 281-W molecular core. Its salient features are:

- A Class I spectral energy distribution.
- Foreground interstellar, molecular core, and circumstellar extinction amounting to \(A_V \approx 20\) mag.

\(^{12}\) We note that VVV-v721 discussed by Guo et al. (2020) may be an exception, though the lightcurve on which their FU Ori claim is based has not yet been presented in the literature. We show the WISE+NEOWISE lightcurve for this source in the appendix.
A large-amplitude photometric rise that was detected in the PGIR time-domain survey, and emphasized by comparing the recent $J$-band imaging photometry with the lack of a $J$-band detection at the same position two decades ago in the 2MASS all-sky photometric survey.

Extended nebulosity in our new $K_s$-band imaging, that was not present in 1990’s images at the same wavelength, with a cometary type structure $\sim 14,000$ AU in size.

A measured 10-15 year photometric brightening trend exhibited in $3 - 5 \mu$m Spitzer + WISE + NEOWISE data, accumulating a total mid-infrared brightness increase of $>5$ mag.

Steepened mid-infrared brightening during 2019 that was coincident with source detection at $J$-band.

Consistent rise rates during 2018-2020 in the mid-infrared NEOWISE lightcurve, and 2019-2020 in the near-infrared PGIR lightcurve, amounting to $-0.12$ mag/month.

A flattening of the lightcurve from its rise phase to a plateau in 2020. The peak luminosity is estimated at a modest 10-12 $L_\odot$.

A near-infrared absorption line spectrum showing hydrogen line, metal line, and molecular band absorption, indicative of a “mixed temperature” spectrum.

Outflow as evidenced by the He I 10830 Å profile.

We conclude that PGIR 20dc1 is a bona fide FU Ori star. The object warrants further study, especially at high spectral dispersion, as its outburst continues to develop.

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Facilities: Palomar Gattini IR, ZTF, Keck/NIRES, Keck/DEIMOS, Spitzer, WISE, NEOWISE, IRSA

APPENDIX

The source VVV-v721 (16:39:48.77 -45:48:47.96) was discussed by Guo et al. (2020) as an FU Ori object based on spectroscopic follow-up of a near-infrared lightcurve from the VVV survey. However, a lightcurve supporting the claim of an outburst has not yet appeared in the literature. We show the NEOWISE photometry in Figure 7, which indeed indicates a photometric brightening has occurred within the past decade. The amplitude of the brightening appears modest in the mid-infrared, but is reportedly larger in the near-infrared.

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Figure 7. Available mid-infrared photometry from WISE+NEOWISE for the source VVV-v721.

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