McNEIL’S NEBULA IN ORION: THE OUTBURST HISTORY

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ABSTRACT

We present a sequence of I-band images obtained at the Venezuela 1 m Schmidt telescope during the outburst of the nebula recently discovered by J. W. McNeil in the Orion L1630 molecular cloud. We derive photometry spanning the preoutburst state and the brightening itself, which is a unique record including 14 epochs and spanning a timescale of ~5 years. We constrain the beginning of the outburst at some time between 2003 October 28 and November 15. The light curve of the object at the vertex of the nebula, the likely exciting source of the outburst, reveals that it has brightened ~5 mag in about 4 months. The timescale for the nebula to develop is consistent with the light-travel time, indicating that we are observing light from the central source scattered by the ambient cloud into the line of sight. We also show recent FLWO optical spectroscopy of the exciting source and of the nearby HH 22. The spectrum of the source is highly reddened; in contrast, the spectrum of HH 22 shows a shock spectrum superposed on a continuum, most likely the result of reflected light from the exciting source reaching the HH object through a much less reddened path. The blue portion of this spectrum is consistent with an early B spectral type, similar to the early outburst spectrum of the FU Orionis variable star V1057 Cygni; we estimate a luminosity of L ~ 219 L☉. The eruptive behavior of McNeil’s Nebula, its spectroscopic characteristics and luminosity, suggest that we may be witnessing an FU Ori event on its way to maximum. By further monitoring this object, we will be able decide whether or not it qualifies as a member of this rare class of objects.

Subject headings: ISM: Herbig-Haro objects — stars: formation — stars: pre–main-sequence — stars: variables: other

1. INTRODUCTION

On 2004 February 9, the discovery of a new nebula, roughly 12° south of the reflection nebula NGC 2068 (M78) in the L1630 molecular cloud of the Orion star-forming complex, was announced by McNeil (2004). The region surrounding the newly revealed object contains a number of pre–main-sequence stars as well as Herbig-Haro objects HH 22 and HH 23 (Eislöeffel & Mundt 1997). The source IRAS 05436–0007 (Clark 1991) is located at the vertex of the new nebula but was not identified by Clark as a young object. The Two Micron All Sky Survey (2MASS) images show an extremely red source at this position (J05461313−0006048), but no object is visible at optical wavelengths in Palomar Observatory Sky Survey plates. More recently, dust continuum imaging of this region by Lis, Menten, & Zylka (1999) revealed several sources at 350 and 1300 μm. They suggest that their source LMZ 12, spatially coincident with IRAS 05436–0007, is a Class 0 source with Lbol ≈ 2.7 L☉ and is the probable exciting source of HH 23, located ~2.5 north of the new nebula.

This new nebula was made widely known by B. Reipurth’s announcement in the Star Formation Newsletter 136. In a follow-up study, Reipurth & Aspin (2004) indicate that the object brightened by ~3 mag in the near-infrared and that its optical and K-band spectra show a certain resemblance to EXors. On the other hand, the object may be undergoing an FU Orionis-type eruption, which would imply a larger variation in brightness and a longer period at maximum light (Herbig 1977). To discriminate between these possibilities, both preoutburst and postoutburst observations are needed.

We report here optical images, photometry and spectroscopy of McNeil’s Nebula, previous to its brightening and during the outburst itself. These observations span ~5 years, with a particularly good coverage of the time when the outburst started. The observations were obtained during a sensitive optical variability study spanning most of the Orion OB1 association (Briceno et al. 2001).

2. OBSERVATIONS AND DATA ANALYSIS

Our large-scale photometric variability study of the Orion OB1 association (see Briceno et al. 2001 for details) has been carried out with the QuEST camera on the 1 m Schmidt telescope at the Llano del Hato National Astronomical Observatory in Venezuela (see Baltay et al. 2002 for details of the instrument). The camera consists of 16 (in a 4 × 4 array) front-illuminated 2048 × 2048 CCDs with 15 μm pixels, although only three rows of four CCDs are presently operational; the plate scale is 1’03 pixel−1. The instrument is optimized to work
TABLE 1
CIDA-SCHMIDT I-BAND PHOTOMETRY

| UT DATE | SCAN | UT | JULIAN DATE | I_c | σ(I_c) |
|---------|------|----|-------------|-----|--------|
| 1999 Jan 9 | 528 | 6:18:43 | 2451187.7630 | 18.44 | 0.11 |
| 1999 Dec 18 | 503 | 4:10:58 | 2451530.6743 | 20.27 | 0.52 |
| 2000 Jan 4 | 504 | 6:39:32 | 2451530.7775 | 19.89 | 0.42 |
| 2002 Nov 1 | 503 | 8:05:18 | 2452579.8370 | 18.69 | 0.45 |
| 2003 Jan 29 | 504 | 9:35:02 | 2452579.8993 | 18.82 | 0.41 |
| 2003 Oct 25 | 550 | 5:26:15 | 2452937.7266 | 17.99 | 0.08 |
| 2003 Oct 28 | 501 | 8:54:00 | 2452940.8708 | 17.91 | 0.08 |
| 2003 Nov 15 | 500 | 5:46:19 | 2452958.7405 | 17.34 | 0.07 |
| 2003 Nov 27 | 501 | 6:28:19 | 2452958.7697 | 17.40 | 0.07 |
| 2003 Nov 27 | 502 | 5:31:12 | 2452970.7300 | 16.87 | 0.03 |
| 2003 Nov 28 | 511 | 4:48:12 | 2452971.7001 | 16.71 | 0.07 |
| 2003 Dec 15 | 512 | 5:34:12 | 2452971.7321 | 16.72 | 0.04 |
| 2003 Dec 26 | 501 | 4:40:00 | 2452988.6944 | 15.38 | 0.02 |
| 2004 Jan 21 | 502 | 5:26:34 | 2452988.7268 | 15.38 | 0.02 |
| 2004 Jan 27 | 500 | 5:22:04 | 2452997.7237 | 15.30 | 0.02 |
| 2004 Jan 30 | 501 | 3:44:00 | 2453003.6556 | 14.81 | 0.03 |
| 2004 Jan 21 | 550 | 2:00:00 | 2453025.5833 | 14.83 | 0.02 |
| 2004 Jan 27 | 551 | 3:26:50 | 2453031.6436 | 14.68 | 0.03 |
| 2004 Jan 30 | 552 | 4:10:00 | 2453031.6736 | 14.65 | 0.04 |
| 2004 Feb 26 | 3:06:00 | 2453061.9208 | 14.40 | 0.08 |

* FLWO 1.2 m + 4-Shooter CCD mosaic camera observation (combination of four 60 s exposures).

In drift-scan mode along strips of the sky, 2.3° wide, at constant declination. Each row of four CCDs is fitted with a different filter. The equivalent exposure time (time the object takes to cross a chip at δ = 0°) is 140 s.

The region we have been monitoring since 1999 January is centered at δ = +170° and spans the range from α = 5.8° to 5.48°. We used one V and two I filters to cover the three good rows of CCDs. Given the location of the source of McNeil’s Nebula (α2000 = 5°46′13.1, δ2000 = −0°6′5′′), and because the V filter is located in the westernmost part of the array, we detected the nebula only in the I band at the very end of most scans.

We were able to recover the nebula in 19 observations on 14 different nights, from 1999 January 9 to 2004 January 28 (Table 1). We obtained an additional I-band observation on 2004 February 26 with the 4-Shooter CCD mosaic camera installed on the SAO 1.2 m telescope on Mount Hopkins, Arizona. Thus, our data set spans 1874 days and includes the period when the nebula began to brighten up. All observations were obtained at an air mass of ~1, and the seeing ranged from ~2‘ to 3.5’. The reduction and processing of the Schmidt data were done with custom-made automated software (see Vivas et al. 2004 for details) that produces magnitudes and accurate positions for all point sources in the region, including variability flag. The 4-Shooter images were processed using custom IDL routines.

In Figure 1, we show a sequence of I-band images obtained between 2003 October 25 and 2004 January 26 at Llano del Hato. A faint source is barely visible in 2003 October, and it begins to brighten up significantly between 2003 November 15 and 27 when the nebula begins to be barely detectable to the northwest. The nebula exhibits significant brightening and evolution from this date on, while the source at its vertex continues to get brighter. By 2004 January 20, the object had mostly reached the state it revealed in the discovery and subsequent images.

In order to measure the brightness of the new nebula and its apparent source, we selected 14 reference stars calibrated as secondary standards with Landolt (1992) fields, with magnitudes $I_c = 12–16$ and colors $V-I_c$ ~1.4–3.9; these stars are located near the nebula (≤10°) and have on average 25 measurements spanning 5 years, showing no significant variability over that time frame, thus making them robust comparison stars. We could not use our automated software for the new observations of the nebula because it does not handle photometry of extended objects. Thus, we used standard IRAF routines to perform differential photometry in several parts of the nebula. We measured three different positions within the nebula: A, B, and C, as shown in Figure 2; these were defined as offsets from the star labeled V in Figure 2 (α2000 = 5°46′18.9, δ2000 = −0°5′38′′). In this way, we were able to measure early images when the nebula was barely detected or not seen at all. Because our images had FWHM ~3′, we used an aperture radius of 4′ for comparison stars and locations on the nebula. The region we call A is centered on the nebula vertex, located 1′26′′1 west and 26′′ south from star V. In all images, this object looks like a point source. Our second aperture (B) was centered on the nebulousness just north of the star. Its location is 1′28′′6 west, 18′′1 south from V. Finally, the third aperture (C) was placed on top of the object HH 22, which also brightened during the event (see Fig. 1), centered at 1′12′′1 south, 7′′7 north of V. Since the region immediately surrounding the apertures is filled with nebulosity, we could not use an annulus to measure the sky brightness. Instead,
the sky was measured by taking the average value of small boxes (3 x 3 pixels) in 10–12 different locations outside and near the nebula.

In Figure 3, we show the resulting light curve of A, B, and C. Our data suggest that even in its "quiescent" phase, with a mean magnitude $I_C = 19.1$, source A is variable on timescales of a few years at the 0.7 mag level, with an extreme range of $\leq2$ mag (the nebular structure is not visible in our preoutburst images); this is consistent with reports of this object appearing in an image from 1966, although rather fainter than at present (D. Tytell 2004). By the time of our first 2003 observations on October 25 and 28, source A had brightened by $\sim0.8$ mag compared with 2003 January. But the more dramatic rise in brightness occurred sometime after October 28 and before November 15, when it was 1.8 mag brighter than its mean level. We measured a total increase of $\sim5$ mag in about 4 months. Source B closely traces the behavior of source A after October 2003 but is on average 0.6 mag fainter, and its brightness does not increase significantly until November 27, a delay of roughly 18 days with respect to source A. Source C, spatially coincident with HH 22, is close to our detection threshold of until December 15, when it is clearly visible at $I_C = 18.2$. This represents a delay of $\sim50$ days with respect to source A. Finally, our most recent data from 2004 February 26 strongly suggests that the rate of brightening has diminished. If we assume a distance of 400 pc as for HH 22 and 23 (Anthony-Twarog 1982) and consider the separations A-B = 8.5" (0.016 pc) and A-C = 36.7" (0.071 pc), we derive a light-travel time of 19 days between A and B, and 85 days between A and C. This is consistent with the delays inferred from the light curve in Figure 2 and indicates that we are observing light scattered into the ambient cloud, possibly coming out through a cavity opened in the embedded source’s envelope.

Optical spectra were obtained the night of 2004 February 18 at positions A and C of the new nebula, using the 1.5 m telescope of the FLWO with the FAST Spectrograph for the Tillinghast Telescope (FAST; Fabricant et al. 1998), equipped with the Lor 512 x 2688 CCD. The spectrograph was set up with a 300 groove mm$^{-1}$ grating and 5" wide slit (oriented at P.A. = 90°), yielding 3400 Å of spectral coverage centered at 5500 Å and a resolution of $\sim10$ Å. The spectra were reduced and wavelength-calibrated using the standard IRAF routines. The effective exposure time at each slit position was 1200 s. The spectra were corrected for the relative system response using the IRAF sensfunc task and observations of spectrophotometric standard stars.

Spectra of A and C are shown in the upper panel of Figure 4. The spectrum of A corresponds to a heavily reddened source, in agreement with the $A_v \geq 12$ derived from 2MASS JHK, colors; depending on the spectral type (see below) and reddening law adopted, the continuum in the visual range suggests $A_v \sim 8–10$, which may be underestimated since there may be a significant scattered-light component. The most conspicuous feature is strong emission at Hα. In contrast, the spectrum of C is much flatter, indicating much less reddening; it also exhibits a number of forbidden lines (in particular [O I] λ6300, 6363; [S II] λ6716, 6730; and [N II] λ6548, 6583) and emission in Hβ and Hδ. The blue portion of the spectrum of C shows the higher Balmer lines in absorption; in the lower panel of Figure 4, we compare the blue portion with spectroscopic standard stars. The strength of the Balmer lines is consistent with either an early B or an early F type, as shown in the figure. However, the absence of the G band and the weakness of Ca II K favor an early B spectrum.

We suggest that we have here a situation similar to the case of the embedded FU Ori object L1551, in which the optical spectrum of the object was obtained by observing its light reflected by the nearby object HH 102 (Mundt et al. 1985). If the line of sight from A to C has been cleared out by the outflow that created HH 22 at the wind-cloud interaction region, then the spectrum of A that reaches C is much less reddened than that in Earth’s direction. The spectrum of C consists of an emission-line spectrum, arising mostly in situ from the shock front(s), plus the reflected, lightly reddened spectrum of A.

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8 See http://skyandtelescope.com/news.
Fig. 4.—FAST spectra. In the upper panel, we show the spectra of sources A (the exciting star) and C (at the location of HH 22); a detail of the region around Hα is shown in the inset. The lower panel contains an expanded view of the blue end of the spectrum of C, showing the higher Balmer lines clearly in absorption. For comparison purposes, we show spectra of several standard stars.

Thus, the spectrum of C gives us direct information of the spectrum of the driving source, which in the blue appears to be close to that of an early B star.

3. DISCUSSION

The behavior of McNeil’s Nebula is reminiscent of the early evolution of the outbursts of FU Ori and V1057 Cyg (Herbig 1977). The optical (red) rise of McNeil’s Nebula, ~5 mag in about a third of a year, is not much different than the early rise of these two objects, prototypical of the FUor class; moreover, the rise time of another FUor, V1515 Cyg, was much longer, indicating that the rate of brightening is not a universal quality among these objects. Like the McNeil object, V1057 Cyg initially showed a P Cygni profile on strong Hα emission (see inset in Fig. 4), evolving into stronger (blueshifted) absorption later on. Strong absorption in the upper Balmer lines was also present in spectra of V1057 Cyg, classified as B3 by Welin (1971). However, the lack of He i lines lead Herbig to assign an approximate type of early A (Herbig 1977). Herbig also noted the presence of wide emission at the Ca ii resonance lines, which lead to a very weak Ca ii 3933 Å absorption; this is also consistent with our optical spectra.

The eruptive behavior suggests that this may be an FU Ori object on its way to maximum or possibly a member of the so-called class of EXors (Herbig 1977), which exhibit similar or smaller increases in optical brightness but last shorter periods of time. Continued monitoring should better help distinguish between these possibilities. Given the small number of objects in the FUor and EXor classes, it may be that there exists a continuum of outburst behavior that will be filled in by the discovery of additional objects. We note that at its recent brightness of $I_c = 14.4$, assuming $A_v = 7.2$, a distance of 400 pc, and adopting an A0 spectral type as a compromise between the range of spectral types we inferred before, the system luminosity is $L \sim 219 L_\odot$ (and would be higher if the intrinsic spectral range were earlier); this large luminosity is more similar to FUors than EXors.

The eruptive mechanism of FUors, and likely also that of EXors, is thought to be rapid outbursts in disk accretion (Hartmann & Kenyon 1996), possibly driven by the pileup of material in a disk due to rapid protostellar envelope infall (Kenyon & Hartmann 1991). The estimated bolometric luminosity $L_{bol} \approx 2.7 L_\odot$ and a spectral energy distribution like that of a Class 0 source (Lis et al. 1999) are consistent with the preoutburst object being a low-mass protostar. This object looks more similar to FUors, which are often highly embedded (Hartmann & Kenyon 1996), than to EXors, which seem to be much less extincted. This very interesting source warrants further monitoring to help determine its true nature.

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