V1647 ORIONIS: REINVIgorATED ACCRETion AND THE RE-APPEARANCE OF MCNEIL’S NEBULA

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ABSTRACT

In late 2003, the young eruptive variable star V1647 Orionis optically brightened by over 5 mag, stayed bright for around 26 months, and then declined to its pre-outburst level. In 2008 August, the star was reported to have unexpectedly brightened yet again and we herein present the first detailed observations of this new outburst. Photometrically, the star is now as bright as it ever was following the 2003 eruption. Spectroscopically, a pronounced P Cygni profile is again seen in Hα with an absorption trough extending to −700 km s⁻¹. In the near-infrared, the spectrum now possesses very weak CO overtone bandhead absorption in contrast to the strong bandhead emission seen soon after the 2003 event. Water vapor absorption is also much stronger than previously seen. We discuss the current outburst below and relate it to the earlier event.

Key words: circumstellar matter – stars: formation – stars: individual (V1647 Ori)

1. INTRODUCTION

When V1647 Orionis went into outburst in the fall of 2003, it brightly illuminated a monopolar reflection nebula subsequently designated McNeil’s Nebula (McNeil 2004). The young star itself increased in optical and near-infrared (NIR, K band) brightness by around 5 and 3 mag, respectively, and sparked a worldwide effort to study the details of this rare type of eruption. To date, this has resulted in over 50 research papers which relate the characteristics of the star and nebula from the time of its detection to the time when it had faded to its pre-outburst optical brightness (in 2006 February). The reader is referred to the most recent publication on V1647 Ori (Aspin et al. 2008, henceforth ABR08) for a comprehensive list of previous work.

It has been speculated that V1647 Ori may be a new example of the class of young variable stars designated “FUor” after the class progenitor, FU Orionis (Ambartsumian 1971). Only about 10 so-called “classical” FUors (those that have been directly observed to optically brighten over a period of a few weeks to a few months) have so far been found. A comprehensive review of the properties of FUors was given by Hartmann & Kenyon (1996); however, it is important to relate here the main characteristics defining this group; (1) an observed rise in optical brightness of around 5–6 mag; (2) an optical spectrum indicative of a G- to F-type supergiant star; (3) an NIR K-band spectrum typical of an M-type giant; (4) the star remains in an elevated state for many years, even decades—FU Ori has declined little in over the 70 years since its discovery (Herbig 1966, 1977); (5) an Hα line in emission with an associated blueshifted absorption component (i.e., a P Cygni profile); and (6) an associated, generally curving, reflection nebula. What has been gleamed with regard to V1647 Ori, however, is somewhat contradictory to these definitive characteristics in that it had a relatively short outburst period (approximately 26 months), its optical and NIR outburst spectra possessed strong atomic and molecular emission features, and the eruption was shown to be repetitive—Aspin et al. (2006) described an earlier event commencing in 1966. Such properties have more in common with those observed in the “EXor” class of eruptive variables, named after their class progenitor, EX Lupi (Herbig 1989).

It was expected that the next eruption of V1647 Ori would be ∼37 years after the 2003 event, assuming the timescale between the 1966 and 2003 events was typical. However, in 2008 late August, some 18 months after the fading of the 2003 outburst, V1647 Ori had brightened in the red optical (≈2.2 μm) to around 120th magnitude, raising questions about the nature of the eruption.

2. OBSERVATIONS AND DATA REDUCTION

Below we present new data taken on four different telescopes and with five different instruments. Optical R-band images (see Figure 1) were obtained on the University of Hawaii (UH) 2.2 m telescope on UT 2008 September 1 using the Tektronix 2K × 2K CCD camera (Tek2K). The on-source exposure time was 120 s and seeing was ∼0.7″. The images were calibrated by using a sequence of six field stars described in C. Aspin, G. H. Herbig, & B. Reipurth (2009, in preparation; henceforth AHR09).

Optical images were also obtained on Gemini-South using the Gemini Multi-Object Spectrograph (GMOS; Davies et al.
The middle-right image was taken in the same R filter in 2008, soon after the recent brightening of the star and the re-appearance of McNeil’s Nebula. The right image is a difference image, 2008–2004. In this image, white is more flux in 2008, black is more flux in 2004. We note that V1647 Ori is the pointlike object at the apex of the monopolar reflection nebula extending northward. The images were scaled to result in the cancellation of the faint binary star at the bottom of the image.

In Figure 1, we show a comparison of red optical images of V1647 Ori from three different epochs. The left image is from UT 2004 September 3 and was taken with an SDSS r′ filter using GMOS. This was around 10–11 months after the 2003 outburst of V1647 Ori was first detected (McNeil 2004) and V1647 Ori had a magnitude of r′ = 17.8. The middle-left image shows the same region of sky but was taken on UT 2006 December 22 using a Johnson R filter with the UH Tek2K camera. At the time of these observations, V1647 Ori had been at its pre-outburst (red optical) brightness of r′ = 23.3 for around 10 months. The middle right is our recent UH Tek2K image detailed in Section 2. In this image, V1647 Ori has an optical brightness of R = 17.3. Comparing the left and middle-right images, we note that both V1647 Ori and its associated nebula are strongly visible. However, in the middle-left image, both the star and the nebula are only faintly visible. The bright knot visible in the middle-left image (top and left of the center) is the Herbig–Haro object, HH 22. We note that the optical brightness of V1647 Ori in the 2004 and 2008 images is similar as is the brightness and morphology of McNeil’s Nebula. The far-right image shows the difference between the 2004 and 2008 images with white implying that the object was brighter in 2008, and black meaning brighter in 2004. The images were scaled prior to subtraction to give the same signal in the faint binary system near the bottom (and left of the center) of the images. Clearly, there are significant differences in brightness between the two epochs suggesting that in 2008 the reflection nebula is illuminated in a somewhat different manner than in 2004. This suggests that dust obscuration close to V1647 Ori may play an important role in defining the observed morphology of the nebula.

Photometric observations of V1647 Ori from the optical through MIR are shown in Table 1. Optical and NIR colors are also given. Within the associated uncertainties, the optical through NIR brightness values for V1647 Ori are comparable to those measured in 2004 February when the source was last observed to have brightened significantly (Reipurth & Aspin 2004).

We present our new optical spectrum of V1647 Ori in Figure 2 (bottom). We additionally show similar spectra from 2004 October (top) and 2007 February (middle) for direct comparison. In 2004 October, V1647 Ori was some 11–12 months into its eruption and had not yet started to decline in optical brightness. In 2007 February, the star had been at its

1997; Hook et al. 2004) on UT 2008 September 22. The Sloan Digital Sky Survey (SDSS) g′, r′, i′, and z′ filters were used and the on-source exposure times were 240, 120, 120, and 80 s, respectively. Details of the photometric calibration can be found in AHR09. Seeing during the observations was ∼0′.6.

Optical spectroscopy was obtained on the UH 2.2 m telescope on UT 2008 August 31 using the dual-channel integral-field unit (IFU) spectrograph, SNIFS (Aldering et al. 2002; Lantz et al. 2004). The 6″ × 6″ field of view of the SNIFS spectrograph is filled with a 15 × 15 grid of lenslet-defined spatial elements, each sampling ∼0′.4. The data were reduced by the SNIFS reduction pipeline (Aldering et al. 2006). The spectral resolution of the final spectrum was R ∼ 1850 which was extracted from the IFU cube using a wavelength-dependent point-spread function fitting procedure (Aldering et al. 2006). Wavelength calibration was performed using the SNIFS internal calibration unit, and flux calibration was performed using observations of spectrophotometric standards.

An optical spectrum was also obtained on Gemini-South using GMOS on UT September 22. We used the R400 grating and a 0′′.75 slit giving an effective spectral resolution of R ∼ 1900. Data were taken in nod-and-shuffle mode to aid in the removal of the bright red optical sky emission lines.

NIR spectroscopy was obtained on the NASA Infrared Telescope Facility (IRTF) telescope on UT 2008 September 4 using the facility’s NIR spectrograph SpeX (Rayner et al. 2003). The cross-dispersed (XD) mode was used and observations were acquired in both the short- and long-XD settings. The data were reduced using the SpeX IDL package (Cushing et al. 2004). Telluric correction and flux calibration were performed using the A0 V telluric standard star HD 39985. Conditions were clear and the seeing stable during the target and standard observations and hence we consider the flux calibration good to the 10% level.

Mid-IR (MIR) imaging was obtained on Gemini-South on UT 2008 September 13 with T-ReCS (Telesco et al. 1998) using broad N′ (λc = 11.2 μm) and narrow Qa (λc = 18.30 μm) filters. Conditions were clear, dry, and stable throughout the observations, and photometric calibration was performed using similar observations of the bright “Cohen” standard star (Cohen et al. 1999) HD39400 (N′ = 1.534, Qa = 1.434).

NIR images were obtained on the WIYN 3.5 m telescope on UT 2008 September 16. The WHIRC NIR camera (Meixner et al. 2008) was used with standard J, H, and Ks filters. Flux calibration was achieved using observations of the UKIRT faint standard star FS 07 (Hunt et al. 1998).
pre-outburst optical brightness for around one year. In all three spectra, Hα is in emission although only in 2004 October and 2008 August did it show a blueshifted absorption component (a P Cygni profile). On both these dates, the blueshifted Hα absorption extended to approximately −700 km s\(^{-1}\), although in 2008 August the depth of the absorption is less than in 2004 October. The full width at half-maximum (FWHM) of the Hα emission is large with the line wings extending to around ±1000 km s\(^{-1}\). This is somewhat larger than observed at the start of the 2004 event (i.e., ~750 km s\(^{-1}\), see AHRO9 for more details) suggesting the physical conditions in the H emission region are somewhat more extreme. Also present in the 2008 August spectrum are the Ca ii triplet lines in emission. The ratios of these lines (1.5:2:1.7) implying that, unlike the emission seen in 2007 February (with ratios 1.7:2:1.9), conditions in the Ca ii emission region have become optically thick producing saturated line emission. The Ca ii emission lines are discussed in more detail in ABR08. Also present in our recent spectrum are O i (6300 Å) in emission, and O i (7773 Å) in absorption. Other weak features may be present but, with the spectral resolution obtained with SNIFS, it is difficult to determine if they are real. Included in Table 2 are details of the optical spectral features present. Two lines that are conspicuously absent are the [S ii] lines at 6717 and 6731 Å which were present in 2007 February. This is likely due to the already weak lines (see ABR08) being masked by the addition of strong continuum (accretion) emission which was not present in the 2007 February spectrum. Finally, we note that the SNIFS acquisition image of V1647 Ori gave a magnitude of V = 18.1.

Figure 3 shows the SpeX NIR spectrum of V1647 Ori (bottom). As in the optical, we also show spectra from two other epochs, in this case 2007 February (middle) and 2004 December (top). Present in the 2008 August NIR spectrum are the atomic emission lines of He i (1.083 μm, P Cygni profile), Paβ (1.282 μm), weak [Fe ii] (1.644 μm), He i (2.058 μm, P Cygni profile), Brγ (2.166 μm), and Brα (4.051 μm). Details of these features are given in Table 2. The molecular CO overtone bandheads longward of 2.294 μm are weakly in absorption in 2007 February, very weakly in absorption in 2008 August, while in 2004 October they were strongly in emission. The water vapor absorption bands, at 1.4, 1.9, and 2.5 μm, are strongly in absorption, and appear much deeper in 2008 August than in either 2007 February or 2004 December. The other broad feature seen in 2008 August is the water ice absorption band, centered at around 3 μm. It appears somewhat different in shape in 2008 August with respect to the two earlier spectra with a less rounded minimum and a more gradual increase back to the continuum on the long-wavelength side. Finally, the 2008 August spectrum shows the presence of the 4.674 μm CO ice absorption band (not included in the plot shown in Figure 3). This band was previously observed in V1647 Ori by Vacca.
et al. (2004), Rettig et al. (2005), and Gibb et al. (2006). Rettig et al. modeled the band shape using polar and apolar CO ice and found that a predominantly apolar CO matrix ice best fitted the 2004 February data with a temperature of $<20$ K. Their conclusion was that the line-of-sight CO ice had not been thermally processed and was consistent with that found toward quiescent dark clouds and regions of low-mass star formation. A qualitative comparison of the band shape in our 2008 August spectrum with that in the 2004 February spectrum of Vacca et al. (2004) suggests that little has changed in the characteristics of the CO ice absorption in the intervening four years.

Using the Paβ and Brγ line fluxes, we can estimate mass accretion luminosities ($L_{\text{acc}}$) and rates ($\log(M_{\odot} \text{ yr}^{-1})$) in a manner similar to that presented in ABR08. Using the relationships defined by Muzerolle et al. (1998) and Gullbring et al. (1998), we find that in 2008 August the line fluxes shown in Table 2 resulted in values of $L_{\text{acc}} = 1.42 L_{\odot}$ and $\log(M_{\odot} \text{ yr}^{-1}) = -6.28$ for Paβ, and $L_{\text{acc}} = 12 L_{\odot}$ and $\log(M_{\odot} \text{ yr}^{-1}) = -5.34$ for Brγ. This assumes a stellar temperature of $T_{\text{eff}} = 3800$ K, a stellar luminosity of $L_{*} = 4.9 L_{\odot}$, and an inner radius for the accretion disk of $R_{\text{in}} = 5 R_{*}$ as in ABR08. For the 2008 August fluxes, we also assumed a visual extinction of $A_{V} = 6$ mag. This was determined by dereddening the observed NIR ($J$) and $K$ colors of V1647 Ori to typical T Tauri star values as in ABR08 (see their Figures 13 and 14). We note that the values of $L_{\text{acc}}$ and $\log(M_{\odot} \text{ yr}^{-1})$ derived from Paβ and Brγ are inconsistent, being larger from Brγ by factors of $\sim 8$ and $\sim 9$, respectively. No value of $A_{V}$ resulted in similar values from the two lines. We can perhaps attribute this difference to the emission in Paβ being optically thick, while in Brγ the emission is less so. The ratio of the dereddened ($A_{V} = 6$) fluxes, Paβ/Brγ, is $\sim 1$ which, from the observations and analysis shown in Figure 15 from Muzerolle et al. (2001), is a factor of $\sim 5$ times smaller than that observed in typical “quiet” classical T Tauri stars. We note that in 2007 February, when V1647 Ori was supposedly in quiescence, ABR08 derived values of $\sim 4L_{\odot}$ and $\sim 6$ (using the same physical parameters as above with $A_{V} = 9$) from both lines, and a line ratio of $\sim 5$. Clearly, the changes observed in $L_{\text{acc}}$ and $\log(M_{\odot} \text{ yr}^{-1})$ warrant a more detailed investigation.

Our MIR imaging of V1647 Ori showed only a point source and hence is not explicitly presented here. However, we have extracted photometric values from these data and can compare them to earlier measurements. We find that the integrated flux from V1647 Ori at $N'$ and $Qa$ is 3.8 and 6.6 Jy, respectively. Similar observations of V1647 Ori in 2007 February, when the star had faded to its pre-outburst optical brightness, gave $N'$ and $Qa$ fluxes of 0.23 and 0.44 Jy, respectively (ABR08). Earlier measurements quoted by Andrews et al. (2004) showed V1647 Ori to have an 11.3 $\mu$m flux of $\sim 10$ Jy. The latter observations were taken soon after the source was discovered by J. McNeil, specifically in 2004 March. Our $N'$ flux of 3.8 Jy is a factor of

![Figure 3. NIR 1–4.2 $\mu$m SpeX spectrum of V1647 Ori taken on UT 2008 August 31 (bottom panels). For comparison, we also show the same wavelength range from SpeX spectra from UT 2007 February 21 (middle panels) and UT 2004 December 10 (top panels). The main spectral features are identified. Features present are water vapor absorption bands (in $H, K$, and $K$), water ice absorption (at 3 $\mu$m), and emission lines of Paβ (at 1.282 $\mu$m), weak Fe II (at 1.644 $\mu$m), He I (at 2.058 $\mu$m), Brγ (at 2.166 $\mu$m), and Brδ (at 4.051 $\mu$m). The right three panels zoom into the $K$-band region of the three spectra. Note the CO bandheads (at 2.294 $\mu$m) are in emission in 2004, are weakly in absorption in 2007, and perhaps very weakly in absorption in 2008.](image-url)
2.6 times smaller than the 2004 outburst value and 16.5 times larger than the quiescent phase flux. At 18.6 μm (Qa), our flux measurement from 2008 September is 15 times the flux observed in 2007. Thus, the ratio of N/Qa flux in 2008 September is the same (within the associated uncertainties) as in 2007 February at around 0.55 times.

4. SUMMARY

What we can conclude about the 2008 late August reappearance of V1647 Ori and McNeil’s nebula is as follows.

1. In the optical, V1647 Ori and McNeil’s Nebula appear photometrically and morphologically similar to when the source was first observed in 2004, i.e., shortly after the eruption occurred.

2. In the NIR, V1647 Ori appears photometrically similar to 2004 February. Spectroscopically, unlike at the start of the 2003 event, CO overtone emission is not observed. Brγ and Paβ emission are, however, present. Strong water vapor bands are also seen.

3. The values of \( L_{\text{acc}} \) and \( \log(M_{\odot} \text{ yr}^{-1}) \) derived from the dereddened Brγ flux (12L⊙ and −5.3, respectively) are of a similar order to those found soon after the 2004 outburst (Muzerolle et al. 2005).

Our qualitative interpretation of the results presented above (for the current eruption, the appearance of V1647 Ori in 2007 as described by ABR08, and for the 2003 October eruption as described by AHR09) can be summarized as follows. We believe that the massive accretion event that occurred in 2003 did not actually terminate in 2006 as previously discussed, but only declined in intensity. This is supported by the high level of accretion found in 2007 February by ABR08, specifically \( \log(M_{\odot} \text{ yr}^{-1}) \sim -6 \). We suggest that the \(-6\) mag optical fading of V1647 Ori between late 2005 and early 2006 was the result of not only a factor of 10 reduction in accretion luminosity (Muzerolle et al. 2005) derived a value of \(-5\), but also the reformation of dust in the immediate circumstellar environment of the star which had been sublimated by the intense radiation field from the 2003 accretion burst. We add further support for this speculative interpretation by noting that the change in \( A_V \) observed between 2004 December and 2005 December (see Figure 14 of ABR08) was of a similar order. In early 2008, we consider that a second burst of accretion again sublimated circumstellar dust and resulted in the current \(-6\) mag brightening of V1647 Ori.

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