V1647 ORIONIS: KECK/NIRSPEC 2 μm ECHELLE OBSERVATIONS

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ABSTRACT

We present new Keck II NIRSPEC high-spectral resolution 2 μm echelle observations of the young eruptive variable star V1647 Orionis. This star went into outburst in late 2003 and faded to its pre-outburst brightness after approximately 26 months. V1647 Orionis is the illuminating star of McNeil’s Nebula and is located near M 78 in the Lynds 1630 dark cloud. Our spectra have a resolving power of approximately 18,000 and allow us to study in detail the weak absorption features present on the strong near-IR veiled continuum. An analysis of the echelle orders containing Mg i (2.1066 μm) and Al i (2.1099 μm), Brγ (2.1661 μm), the Na i doublet (2.206 and 2.209 μm), and the CO overtone bandhead (2.2935 μm) gives us considerable information on the physical and geometric characteristics of the regions producing these spectral features. We find that, at high spectral resolution, V1647 Orionis in quiescence resembles a significant number of FU Orionis type eruptive variables and does not appear similar to the quiescent EX Lupi variables observed. This correspondence is discussed and implications for the evolutionary state of the star are considered.

Key words: accretion, accretion disks – reflection nebulae – stars: individual (V1647 Ori)

1. INTRODUCTION

The 2003–2006 outburst of the partly embedded, pre–main-sequence star V1647 Orionis has provided a plethora of information on the nature of eruptive variables and the physical changes undergone by a star during such an event. V1647 Ori, the illuminating source of McNeil’s Nebula (McNeil 2004) located near M 78 in the Lynds 1630 dark cloud, brightened by over 5 magnitudes in the optical (Bricenho et al. 2004; Reipurth & Aspin 2004a) and 3 magnitudes in the near-IR (NIR; Reipurth & Aspin 2004a; Ojha et al. 2004) in the space of a few weeks. The eruption also produced an enhanced H i spectrum highlighted by a high-velocity (∼600 km s−1) blueshifted Hα absorption component creating a P Cygni profile (Reipurth & Aspin 2004a; Walter et al. 2004; Fedele et al. 2007). In the NIR, strong v = 2 – 0 CO overtone bandhead emission was observed immediately after outburst (Reipurth & Aspin 2004a; Vacca et al. 2004) which faded as the event progressed to weak absorption (Aspin et al. 2008, henceforth ABR08; Brittain et al. 2007). The pre-outburst, outburst, and post-outburst spectral energy distributions (SEDs) of V1647 Ori was studied by Abraham et al. (2004), Andrews et al. (2004), and ABR08, respectively. Pre-outburst, the SED was that of a flat-spectrum source with an integrated bolometric luminosity (Lbol) of ∼5.6 L⊙. Soon after the outburst occurred, Lbol had risen by a factor 5 to 10. Approximately one year after the optical brightness of the star had returned to its pre-outburst level, V1647 Ori had an Lbol ∼ 9.2 L⊙. This outburst of V1647 Ori was the second documented event for this source: Aspin et al. (2006) studied a previous event, caught on photographic plates and film, from 1966–1967. They concluded that both events were very similar in timescale and amplitude suggesting a common origin for the eruptions. To date, more than 40 refereed publications have been published on the 2003–2006 outburst covering all wavelengths from X-ray to optical to sub-mm and detailing the variability observed. The reader is referred to the list of references in ABR08 for more detailed information on the specific waveband observations.

Numerous authors have attempted to classify the outburst of V1647 Ori as either an FU Orionis (FUor) or EX Lupi (EXor) eruptive event. These designations were first defined and discussed by Herbig (1977, 1989). FUor events are deemed to be long-term (decades) eruptions, commonly commencing with a rapid brightening followed by a slow decline as observed in the class prototype, FU Orionis. EXor eruptions are seen to be shorter term events (typically lasting months) with similar brightening characteristics yet highly variable in decline as observed in the class prototype, EX Lupi (Herbig 1977; Herbig et al. 2001). Much discussion has transpired regarding these two types of outbursts, specifically whether they are the result of the same physical event acting on different timescales, or different triggering mechanisms producing different observed characteristics. In fact, the mechanism by which FUor events are initiated is not yet definitively known, with several mechanisms being proposed. Thermal runaway accretion in a circumstellar accretion disk was considered by Bell & Lin (1994) and Bell et al. (1995), whereas the evolution from envelope accretion to (overloaded) disk magnetospheric accretion was proposed by Hartmann & Kenyon (1985, 1996). Alternatively, a mechanism involving the close approach of a stellar companion in an elliptical orbit which disrupts the inner regions of the accretion disk was described by Bonnell & Bastien (1992) and elaborated on by Reipurth & Aspin (2004b). Finally, Gammie (1996) suggested that perhaps intra-disk gaps modulate accretion bursts. Regarding V1647 Ori, the majority of authors have classified its outburst as an EXor rather than FUor event due to its short duration and observed characteristics. However, it is perhaps not clear that two distinct categories of eruptive events exist, rather a continuum of events may occur with the FUors being at one extreme (longest) and the EXors at the other (shortest). Gibb et al. (2006) and Fedele et al. (2007) also suggested such a scenario. Additionally, perhaps factors such as source age and disk mass may play a role in determining the nature of outbursts.
were acquired using a 4 pixel (0.′′576) wide slit resulting in a pixel-defined spectral resolution, \( R \), of \( \sim 18,000 \) or, at \( 2 \mu \text{m}, \ 16.7 \text{ km s}^{-1} \). The pixel scale was 0′′2 pixel−1 along the 12′ long slit and astronomical seeing was \( \sim 0′′6 \) during the observations. The NIRSPEC grating was positioned to an echelle angle of 61′′89 and a cross-disperser angle of 35′′45 resulting in echelle orders 32–38 falling on the science array. These included the spectral regimes containing Mg i (2.1066 \( \mu \text{m}, \) order 36), Al i (2.1099 \( \mu \text{m}, \) order 36), H i Brγ (2.1661 \( \mu \text{m}, \) order 35), Na i (2.206 and 2.209 \( \mu \text{m}, \) order 34), and the \( v = 2 - 0 \) CO overtone bandhead (2.2935 \( \mu \text{m}, \) order 33). The NIRSPEC-7 blocking filter was also used. The free spectral range of each echelle order was \( \Delta \lambda \simeq \lambda / 67 \) or \( \Delta v \sim 4450 \text{ km s}^{-1} \).

**Table 1**

| Object     | R.A.         | Decl.         | Obs. Date (UT) | S:N^a |
|------------|--------------|---------------|----------------|-------|
| L1551 IRS^b| 04 31 34.1   | +18 08 05     | 2007 Aug 26    | 100   |
| VY Tau     | 04 39 17.4   | +22 47 53     | 2007 Aug 26    | 85    |
| V1118 Ori  | 05 34 44.8   | −05 33 42     | 2008 Jan 26    | 115   |
| NY Ori     | 05 35 35.8   | −05 12 21     | 2008 Jan 26    | 200   |
| V1143 Ori  | 05 38 03.9   | −04 16 43     | 2008 Jan 26    | 50    |
| V883 Ori^b | 05 38 18.1   | −07 02 27     | 2007 Mar 06    | 140   |
| FU Ori^b   | 05 45 22.4   | +09 04 12     | 2007 Mar 06    | 120   |
| V1647 Ori  | 05 46 13.1   | −00 06 05     | 2007 Aug 26    | 200   |
| V1647 Ori  | 05 46 13.1   | −00 06 05     | 2008 Jan 26    | 300   |
| ρ Oph IRS 63^b | 16 31 35.5   | −24 01 28     | 2000 May 30    | 140   |
| Par 21^b   | 19 29 00.7   | +09 38 39     | 2001 Jul 07    | 220   |
| HH381-IRS^b| 20 58 21.4   | +52 29 27     | 2001 Jul 07    | 190   |
| V1057 Cyg  | 20 58 53.7   | +44 15 29     | 2007 Aug 26    | 350   |
| HH354 IRS^b| 22 06 50.7   | +59 02 49     | 2001 Jul 07    | 60    |

Notes.

^a Signal-to-noise ratio in the final spectrum.

^b Observed for, and presented in, Greene et al. (2008).
Figure 3. V1647 Ori Na echelle order (top) together with the same wavelength range from MK standard stars GL 338B (K7 V), GL 402 (M4 V), HR 5150 (M1.5 III), and α Ori (M2 Iab). The spectra have been corrected for the $v_{\text{helio}}$ radial velocity at the time of observation. Although the features seen in the standards are mostly present in V1647 Ori, they are considerably sharper in the MK standards suggesting that they are considerably broadened in V1647 Ori. The bottom dotted line is the α Ori spectrum artificially broadened to simulate the V1647 Ori data. The broadening was performed by smoothing the α Ori spectrum using the IRAF task `splot` and the "s" command. The smoothing used was $\sim 120 \text{ km s}^{-1}$ and gave a good match between the isolated Ti line at 2.224 $\mu$m in both sources. All atomic lines in this wavelength regime are identified at the bottom of the plot.

During the on-sky exposures, the slit was physically stationary and hence was allowed to rotate on the sky during alt-az tracking. Data were acquired in ABBA sequences with the target on the slit at all times and nodded by $\pm 6''$. The total exposure time on V1647 Ori ($m_K \sim 10$) was 20 minutes. Observations of the A0 V star HIP 29881 ($m_K \sim 6.6$) were obtained immediately following the target observations and at a similar airmass to use as a ratio star to remove telluric features. The standard “Lamps ON” (flat, dark, arc) calibration sequence was obtained at the start of the observing night and used for flatfielding and wavelength calibration. Telluric OH emission lines were additionally used to obtain an accurate wavelength calibration. We utilized the telescope autoguider fed by the internal IR camera “SCAM” to keep the targets on the long-slit.

Data reduction was performed using the Starlink FIGARO spectroscopic reduction package (Shortridge et al. 2002). First, AB pairs were subtracted and the resultant images flat-fielded. Next, the programs profile and optextract were used to optimally extract the source spectra. Wavelength calibration was performed using the program arc and then applied to the extracted spectra using the program xcopy. The resultant spectra were then ratioed with the extracted standard star spectrum using program irflux and the flux in Janskys was converted to $W \text{ m}^{-2} \mu m^{-1}$ using program irconv. The Brγ absorption feature in the A0 V standard was removed before application to the target spectra using linear interpolation and program isedit. Due to the width of the Brγ absorption in the standard, some weak telluric absorption features remained in the ratioed target spectrum near 2.1661 $\mu$m. However, since they do not affect the profile of the Brγ emission in V1647 Ori and the Brγ line is corrected for absorption in the telluric standard, further consideration of these features was not undertaken. Finally, the four (ABBA) ratioed, flux-calibrated spectra of V1647 Ori were median filtered to remove noise spikes. This improved the signal-to-noise ratio in the final spectrum by approximately a factor $\times 2$.

We have corrected the final spectra for the $v_{\text{helio}}$ radial velocity component using the values obtained from the IRAF tasks rvcorrect with the UT time of observation to determine the value and specshift to shift the spectra in wavelength by the appropriate amount.

Below, we compare and contrast the V1647 Ori echelle spectral orders with the equivalent data on several classical FUors, FU Ori itself and V1057 Cyg, and two FUor-like objects observed by Reipurth & Aspin (1997) and confirmed as FUors by GAR08. These objects are V883 Ori and L1551 IRS5. The spectra have been corrected for the $v_{\text{helio}}$ radial velocity at the time of observation. The comparison between the features present in these objects is quite remarkable and suggests that V1647 Ori in quiescence and the active FUors have much in common. Again, all atomic features in this wavelength range are identified and additionally the Na doublet at 2.206 and 2.208 $\mu$m are marked with dot–dashed lines through all spectra as an aid to relating features between them.
survey of FUors and EXors undertaken by the authors. Additional data are used from previous observing runs by one of us (T.P.G.). All the data used (with the exception of the \(2.122\) \(\mu m\) line was removed from the L1551 IRS5 Na order prior to the xc analysis. The final spectra of these four orders in which they are produced. These are orders \#36 containing Mg \(\perp\) \((2.1066\) \(\mu m\)) and Al \(\perp\) \((2.1099\) \(\mu m\)), \#35 containing Br\(\gamma\) \((2.1661\) \(\mu m\)), \#34 containing the Na \(\perp\) doublet \((2.206\) and \(2.209\) \(\mu m\)), and \#33 containing the \(\nu = 2 - 0\) CO overtone bandhead \((2.2935\) \(\mu m\)). The final spectra of these four orders for V1647 Ori (2007 August 26) are shown in Figure 1. The top panel shows order \#36, the upper-middle panel order \#35, the lower-middle panel order \#34, and the bottom panel order \#33 and all atomic spectral features present are indicated. Of particular note in these echelle orders is the fact that all spectral features appear broad with respect to the residual sky absorption line at \(\sim 2.1638\) \(\mu m\) (its presence is explained below). We estimate that the unresolved sky absorption line has a full-width half maximum (FWHM) of \(20\) \(km\) \(s^{-1}\). In Figure 2 we show the NIFS Na echelle order to-
Figure 5. Cross-correlation function from the comparison of the V1647 Ori Na echelle order with that of FU Ori (solid line). The sharp, symmetric peak at slightly negative velocity indicates an excellent correlation between these two sources and produces a Tonry & Davis (1979) R value of 11.2. Values above $R = 3$ indicate a significant correlation, the higher the value, the better the correlation. Also shown is the correlation function for the comparison of V1647 Ori and the observed $\alpha$ Ori data (dotted line). Note the lack of any strong peak, indicating a generally poor correlation with $R = 0.6$.

and spectral type (M0 V) for the absorbing region which was assumed to be the stellar photosphere of V1647 Ori.

It is clear from Figure 3 that, compared with MK spectral standard stars, specifically the K7 V dwarf GL 388B, the M4 V dwarf GL 402, the M1.5 III HR 5150, and the M2 Iab supergiant $\alpha$ Ori, the Na order of V1647 Ori is fundamentally different in its spectral characteristics. The data on GL 338B, GL 402, and HR 5150 were taken from Doppmann et al. (2005) who utilized the same NIRSPEC setup as our V1647 Ori observations. The $\alpha$ Ori data are from Wallace & Hinkle (1996) and were taken at a factor $\sim 4$ higher spectral resolution than our NIRSPEC observations. However, they were degraded to match the spectral resolution of our data prior to use. Whereas the MK standards show relatively narrow (almost unresolved) atomic absorption features with FWHM of $\sim 20$ km s$^{-1}$ (the Na lines are pressure broadened in the dwarf spectrum), the features in V1647 Ori are very broad and blended with a FWHM of typically $\sim 120$ km s$^{-1}$.

The significant structure seen in V1647 Ori has little in common with the observed dwarf, giant, or supergiant star spectra and is perhaps more reminiscent of a significantly broadened giant/supergiant, which contain a wealth of molecular lines from their low-surface gravity atmospheres. To investigate this, we have artificially broadened the $\alpha$ Ori spectrum using the smooth feature (“s”) in the IRAF task splot. The dotted line at the bottom of the plot is the $\alpha$ Ori spectrum smoothed to give a Ti $2.224\mu$m line width of $\sim 120$ km s$^{-1}$. As one can see, although the features do not all correlate well with the V1647 Ori spectrum, the general trend and gross shape of the spectra are similar.

In Figure 4 we have plotted the Na order spectrum of V1647 Ori with similar spectra of the classical FUors FU Ori, V1057 Cyg, V883 Ori, and L1551 IRS5 all taken from Greene et al. (2008, henceforth GAR08) with the exception of V1057 Cyg, which was observed on the same night as our first V1647 Ori spectrum. Using the IRAF rv package task rvcorrect, we have corrected the spectra for the appropriate $v_{\text{helio}}$ radial velocity component. The most striking feature of this plot is the fact that all spectra appear remarkably similar, in particular the echelle spectrum of FU Ori itself appears almost identical to that of V1647 Ori. To quantify this similarity, we have performed a cross-correlation (henceforth referred to as xc) analysis of these spectra (and those of the MK standards above) using the IRAF rv package task fxcor and the results are presented in Table 2. The xc value used to determine the correlation between spectra is the Tonry & Davis (1979) R value which gives a measure of the correlation peak height with respect to the average noise in the spectrum for each correlation function derived. The R value is an output parameter of the fxcor task. We note that an R value greater than 3 indicates a significant correlation between spectra and is approximately equivalent to a significance of $\sim 3\sigma$. Therefore, the larger the R value, the better the correlation. We have also included the FUor-like objects HH354 IRS, HH381 IRS, and Par 21 (also taken from GAR08) in the xc analysis. For the sake of brevity, we henceforth refer to both classical FUors and FUor-like objects by the generic name FUors.

4 However, we have not corrected for the difference in molecular cloud radial velocities.
Figure 7. Same plot as in Figure 3 but for the CO bandhead echelle order. The spectra have been corrected for the $v_{\text{helio}}$ radial velocity at the time of observation. The same trends are evident as in the Na order, namely that the lines/bands in V1647 Ori are considerably broadened with respect to the corresponding lines/bands in the MK standards stars.

In echelle order #34, the MK standard stars give very low R values ($R < 1.1$) when cross-correlated with V1647 Ori. Additionally, the broadened $\alpha$ Ori spectrum does not correlate well with V1647 Ori producing $R < 1$. On the other hand, all the FUors (FU Ori, HH1381 IRS, and Pa21) give $R > 12$. The mean R value over the seven FUor observations is $\langle R \rangle = 11.3 \pm 5.2$. Clearly, the uncertainty quoted on $\langle R \rangle$ indicated the range of R values encountered. As a representative plot, we show the xc function for FU Ori (solid line) and $\alpha$ Ori (dotted line) in Figure 5. We used the observed spectra (prior to $v_{\text{helio}}$ correction) in the xc analyses, and hence the velocity shift of the xc peak (for FU Ori) is due to the sum of the difference in $v_{\text{helio}}$ between sources at the times of their observation, and the difference in the velocity of the clouds in which they reside.

In addition to the FUors, we have cross-correlated the echelle spectra of V1647 Ori with a sample of EXor variables and one heavily veiled ($r_K = 3.7$) K5–7 Class I protostar, $\rho$ Oph IRS 63. The latter source was found to have a rotational velocity of $v_{\sin i} \approx 45$ km s$^{-1}$ by Doppmann et al. (2005). Figure 6 shows the Na order for V1647 Ori and four EXors, V1118 Ori, V1143 Ori, NY Ori, and VY Tau. All were observed while they were faint, i.e., not in an eruptive state. The values of R from the xc of these sources with V1647 Ori are in the range 0.8–3.9 with a mean value of $\langle R \rangle = 1.8 \pm 1.2$. Only one source produced an $R > 3$ correlation and therefore a statistically significant result (V1118 Ori, $R = 3.9$). The value of $\langle R \rangle$ for the EXors is therefore over 6× smaller than the corresponding value for the FUors. A visual comparison of the V1647 Ori and EXor spectra shows that although some of the EXor features appear present in V1647 Ori, they are considerably narrower in the EXors (e.g. Ti I at $\sim 2.24$ μm). Artificially broadening the EXor spectra to match the FWHM of typical features in V1647 Ori also results in relatively poor xc values. We also see that the V1647 Ori spectrum possesses considerably more structure than those of the EXors. This is perhaps attributable to the presence of broad molecular bands in V1647 Ori that are not observed in the EXor spectra. We finally note that the xc of V1647 Ori with IRS 63 gave $R \sim 0.6$.

3.2. Echelle Order #33—the CO Overtone Bandhead

A similar comparison can be performed using the echelle order containing the CO overtone bandhead. Figure 7 shows the V1647 Ori observation together with similar observations of the MK standard stars. Again, we have corrected the spectra for the appropriate $v_{\text{helio}}$ radial velocity components. The features seen in the MK standard stars are considerably narrower than those in V1647 Ori and the CO bandhead itself is very broad in V1647 Ori with respect to its profile in the dwarfs, giants, and supergiants. Support for this comes from the comparison of both the slope of the bandheads, and the fact that the individual
Figure 9. Same as Figure 6 but for the echelle order containing the CO overtone bandhead at 2.2935 $\mu$m. The spectra have been corrected for the $v_{\text{helio}}$ radial velocity at the time of observation. Again, the dot–dashed lines identify several absorption lines and are provided to guide the eye between the different spectra. Here, as in Figure 6, the features in V1647 Ori are considerably broader than in the EXors. Also, the CO bandhead is clearly sharper in the EXors than in V1647 Ori.

CO lines longward of the bandhead are blended in V1647 Ori unlike in the MK standards.

A comparison of the CO echelle order of V1647 Ori and the same FUors shown in Figure 4 is presented in Figure 8. As in the Na region comparison, there is considerable correspondence between the features seen in all spectra although there are some obvious differences in line/band broadening, for example, L1551 IRS5 seems less broadened than either V1647 Ori, FU Ori, or V883 Ori. The atomic features in this wavelength range are indicated at the bottom of the plot. However, as with the Na echelle order, there are numerous features that do not correspond to atomic lines even if they are significantly broadened. The spectra of $\alpha$ Ori shown in Figures 3 and 7 have many weak, narrow features. The plot of $\alpha$ Ori from Wallace & Hinkle (1996) together with their Table 2 suggests that the majority of these weaker features correspond to molecular CN. In fact, 600 CN lines are present in the 2–2.4 $\mu$m passband together with 627 from CO rovibrational overtone transitions (longward of 2.2935 $\mu$m). Perhaps molecular CN lines are also present in the V1647 Ori spectrum (as CO lines are).

Quantitatively, we have cross-correlated the V1647 Ori CO spectrum with the MK dwarfs, giants, and supergiants, and all other objects from Table 2. We have performed this xc over two wavelength ranges, first over the whole echelle order (including the CO bandhead), and second over a restricted wavelength range, specifically, 2.27–2.292 $\mu$m (excluding the CO bandhead). The results of the restricted range xc are shown in parentheses immediately following the xc values for the whole echelle order. Since the CO absorption bands are strong and extensive with respect to the atomic lines, we expect that in all objects that possess CO absorption, a significantly higher correlation value will be found when CO is included in the xc. This is borne out by the xc values produced for the MK standards where, over the whole echelle order, a significant correlation of $\langle R \rangle = 9.4 \pm 1.8$ is found. However, for the region shortward of the bandhead, the xc analysis indicates that V1647 Ori correlates less well (although still statistically significant) with the MK standards ($\langle R \rangle = 3.3 \pm 0.7$). Further, as found with the Na order, V1647 Ori correlates very well with all FUors producing $\langle R \rangle = 16.2 \pm 2.9$ and $12.9 \pm 2.1$ for the whole echelle order and the restricted spectral range, respectively. Figure 9 shows the CO order spectra of V1647 Ori and the four EXors. There is clearly more broad structure in the V1647 Ori spectrum than in the EXors and the CO bandhead itself is significantly broader in V1647 Ori. The R values produced by the xc of V1647 Ori with the EXors gives $\langle R \rangle = 9.2 \pm 4.0$ and 4.1 $\pm 1.0$ for the full and restricted spectral region, respectively. Again, as we found for the Na order spectra, the $\langle R \rangle$ value obtained from the xc of V1647 Ori with the FUors is significantly larger ($3.1 \times$) than the mean value obtained for the EXors (over the restricted spectral range not including the CO bandhead). Finally we note that the xc of V1647 Ori with IRS 63 gives values of $R = 13.6$ and 5.0, for the full and restricted spectral regions, respectively.
3.3. Echelle Order #36—the Mg i and Al i Lines

The structure present in echelle order #36 of V1647 Ori is very similar in nature to that in the other orders. The lines are broad and merged and it is difficult to identify discrete features with specific absorption lines. Figure 10 shows the V1647 Ori order #36 spectrum together with the same region from the MK standard stars. As before, the correspondence in features and line widths is minimal. A comparison of the V1647 Ori order #36 spectrum with those of the FUors (Figure 11) shows an excellent agreement in the features present in terms of both location and width. As with the CO order, a comparison with the EXors (Figure 12) shows a much poorer correlation. Expanded views of the region around the (temperature sensitive) Mg i and Al i lines for FUors and EXors are shown in Figures 13 and 14, respectively. Identified on these plots are all atomic (dot-dashed) and molecular CN lines (dotted) present in this region. Since it is not possible to associate atomic lines with all the absorption features present, it may well be that, for example, the two broad absorption dips between 2.107 and 2.1095 μm are broadened and merged molecular CN absorption lines.

The xc of the V1647 Ori order #36 spectrum with the MK standards gave \( \langle R \rangle = 3.3 \pm 3.2 \). Only one star produces a statistically significant correlation, namely, GL 402 with \( R = 9.7 \). A comparison of the spectrum of GL 402 with V1647 Ori shows that several features present in the M4 V star are also present in V1647 Ori, although they are somewhat broader in the latter. This correspondence is lacking in a comparison of the other MK standards to V1647 Ori. For the FUors, the results of the xc with V1647 Ori give R values in a range of 10.5 to 16.9 with \( \langle R \rangle = 12.6 \pm 2.1 \). The same xc with the EXors produces a range of 0.7 to 5.1 with \( \langle R \rangle = 3.8 \pm 1.8 \). As with the CO order, the correlation coefficient value is over 3 \( \times \) larger for the FUors than the EXors.

3.4. Echelle Order #35—the Brγ Line

In Figure 1, echelle order #35 includes Brγ. This line is in emission in V1647 Ori and appears considerably broader than unresolved lines with just the instrumental profile. The FWHM of the Brγ line is \( \sim 150 \text{ km s}^{-1} \) compared to an unresolved line of FWHM \( \sim 17 \text{ km s}^{-1} \). Due to the Brγ absorption in the A0 V telluric standard star, we interpolated across the Brγ absorption in the standard to allow the true strength and profile of the Brγ line in V1647 Ori (and the other objects) to be studied. However, due to the spectral resolution of the data and the significant pressure broadening of the Brγ in the dwarf atmosphere, we had to interpolate from 2.16 to 2.172 μm. This resulted in two strong (and two weak) narrow telluric absorption lines remaining in the V1647 Ori spectrum originating from telluric absorption at \( \sim 2.16344 \) μm and 2.16869 μm. Their presence, however, serves a useful purpose in that they show the width of unresolved spectral features. In addition to being broadened, the V1647 Ori Brγ line profile is a little asymmetric; the long-wavelength side of the profile seems truncated with respect to...
the short-wavelength side. This was also seen in Hα in the 2007 February 21 optical spectrum presented in ABR08 where it was interpreted as possible evidence for the presence of red-shifted Hα absorption from infalling cool gas. However, due to the presence of weak telluric absorption on the red wing of the Brγ feature, this correspondence cannot be made conclusively.

One difference between V1647 Ori and the FUors shown in Figure 15 is that Brγ emission is absent from the FUor spectra. In fact, our high-resolution spectra of the FUors show, in all cases, weak Brγ absorption. This is not obvious in the lower-resolution spectra of these sources from Reipurth & Aspin (1997) due to the weakness of the features. On the other hand, Brγ is either in emission or absent in the EXor spectra shown in Figure 16. In both V1118 Ori and NY Ori, Brγ has a FWHM of $\sim$100 km s$^{-1}$.

### 3.5. Repeat Observations of V1647 Ori

We have related above that NIRSPEC echelle observations of V1647 Ori were acquired at two different epochs separated by six months. The same echelle orders as displayed in Figure 1 are shown in Figure 17, this time for both datasets. The spectral features correlate well in all orders with relatively minor differences. The Brγ emission changed somewhat and weakened between the two observations suggesting that a variation (reduction) in accretion rate occurred. In a subsequent paper we will investigate the temporal variation in accretion rate estimated from Brγ flux since it is beyond the scope of the current work. The R values obtained from an xc of the two spectra range from 17.3 (#36) to 21.5 (#53), strongly supporting the result of the qualitative comparison (see Table 2 for the complete results). It seems therefore that, over this five month period, the structure seen in the 2 μm spectrum of V1647 Ori remains relatively stable with the exception of an implied reduction in accretion.

### 3.6. Cross-Correlation of EXors and MK Standards

In Table 3 we also show the results of the xc of the EXor VY Tau with the other three EXors observed and the MK standards. The correlation values for all orders in each xc are all greater than the three. This implies that the EXors have features in common with each other and, in many cases, many in common with the MK standards. The highest correlation values found from the xc of VY Tau and MK standards was for the correlation with the K7 V star GL 338B. VY Tau has most in common with the EXor V1143 Ori.

### 4. DISCUSSION

Rather than attempt to definitively categorize V1647 Ori in one of the established classifications, we prefer to simply consider the facts that have become apparent from both the above results and results from other recent work. From what we have learned we can state that:
Table 3
Cross-correlations\(^a\)(xc) of VY Tau with Other Objects

| Template Object | R(36)\(^b\,\,c\) | PH(36)\(^d\) | R(34)\(^b\) | PH(34)\(^d\) | R(33)\(^b\,\,c\) | PH(33)\(^d\) | Classification |
|-----------------|-----------------|-------------|-------------|-------------|-----------------|-------------|---------------|
| α Ori           | 4.6             | 0.30        | 10.2        | 0.53        | 10.7(7.0)       | 0.82(0.43)  | M2 Iab (observed) |
| GL 388B         | 14.3            | 0.68        | 22.3        | 0.87        | 10.0(10.2)      | 0.63(0.58)  | K7 V           |
| GL 402          | 13.2            | 0.65        | 14.9        | 0.83        | 19.4(7.3)       | 0.81(0.39)  | M4 V           |
| HR 5150         | 5.5             | 0.37        | 10.3        | 0.59        | 10.3(7.5)       | 0.66(0.43)  | M1.5 III       |
| NY Ori          | 4.5             | 0.40        | 8.2         | 0.42        | 4.0(5.5)        | 0.41(0.43)  | EXor           |
| V1118 Ori       | 5.5             | 0.53        | 6.3         | 0.42        | 5.0(4.6)        | 0.51(0.47)  | EXor           |
| V1143 Ori       | 7.6             | 0.58        | 10.7        | 0.76        | 15.3(5.0)       | 0.78(0.46)  | EXor           |

Notes.
\(^a\) Calculated using IRAF rv package: program fxcor.
\(^b\) Tonry & Davis (1979) R value. \(R > 3\) implies significant correlation.
\(^c\) R value calculated over whole wavelength range and, in parentheses, the wavelength range 2.104 to 2.111 \(\mu m\) including just the Mg\(i\) and Al\(i\) lines.
\(^d\) Fractional peak correlation function height, in range 0–1.0.
\(^e\) R value calculated over whole wavelength range including the CO bandhead and, in parentheses, only the wavelength range 2.27–2.292 \(\mu m\) i.e. excluding the CO bandhead.

Figure 15. Echelle order containing Br\(\gamma\) for V1647 Ori and the four FUors. Only the region around Br\(\gamma\) is shown. The prominent absorption features shortward and longward of Br\(\gamma\) are residual telluric lines due to the interpolation across the Br\(\gamma\) absorption feature in the telluric standard. The spectra have been shifted to correct for \(v_{\text{helio}}\). V1647 Ori shows Br\(\gamma\) emission while all the FUors show Br\(\gamma\) in absorption.

Figure 16. Echelle order containing Br\(\gamma\) for V1647 Ori and the four EXors. Only the region around Br\(\gamma\) is shown. The prominent absorption features shortward and longward of Br\(\gamma\) are residual telluric lines due to the interpolation across the Br\(\gamma\) absorption feature in the telluric standard. The spectra have been shifted to correct for \(v_{\text{helio}}\). V1647 Ori and two of the EXors exhibit Br\(\gamma\) emission while the other two EXors show no Br\(\gamma\) feature.

1. The high-resolution spectra of V1647 Ori do not resemble those of late-type MK standards (dwarfs, giants, and supergiants) nor a typical Class I protostar. This is even the case when the spectra of the MK standards are degraded in resolution to simulate the significant line broadening observed (\(\Delta v \sim 120\, \text{km s}^{-1}\)) in V1647 Ori.

2. The high-resolution NIR spectral properties of V1647 Ori in quiescence do not correlate well with those of known EXors (i.e. NY Ori, V1118 Ori, V1143 Ori, and VY Tau). At lower spectral resolution, EX Lupi itself showed a dwarf-like K-band spectrum with weak Br\(\gamma\) emission during a minor eruption (\(V_{\text{max}} \sim 11.5\)) in 1994 (Herbig et al. 2001).
Additionally, during a more significant outburst in 2008 ($V_{\text{max}} \sim 8$), EX Lupi exhibited strong $K$-band emission from the molecular CO overtone bandheads, and atomic Na I, and Ca I lines (C. Aspin et al. 2009, in preparation). We note that such an emission spectrum was also observed in V1647 Ori soon after outburst (Reipurth & Aspin 2004a; Vacca et al. 2004) and faded, after several months, to a predominantly absorption spectrum.

3. V1647 Ori shows considerable correspondence with several known classical FUors, a fact supported by the high statistical significance of the $x_c$ analyses performed. We note that, whereas the FUors are mostly in elevated eruptive states during the above observations, V1647 Ori was at its pre-outburst optical brightness, some 18 months after its most recent outburst had subsided.

4. ABR08 have shown that the mass accretion rate, one year after the star had supposedly become quiescent, was still considerable, at $\sim 10^{-6} M_\odot$ year$^{-1}$. This suggests that V1647 Ori had not declined to a "classical" T Tauri star (CTTS) state, where the expected accretion rate would be $\sim 10^{-7}$--$10^{-8} M_\odot$ year$^{-1}$, but rather, and more appropriately, a Class I/II state with a typical accretion rate of $\sim 10^{-6}$--$10^{-7} M_\odot$ year$^{-1}$.

5. C. Aspin et al. (2009, in preparation), amongst others, have shown that the optical outburst of V1647 Ori, from its initial brightening in late 2003 to its return to a pre-outburst brightness in early 2006, lasted around 27 months. This timescale is more consistent with an EXor eruption than any known FUor outburst.

6. V1647 Ori had gone into outburst at least one other time, the previous one occurring some 37 years earlier (Aspin et al. 2006). Again, this is consistent with the behavior of EXors and not that of known FUors.

7. The SED of V1647 Ori pre-outburst, during outburst, and post-outburst, resembled those of known FUors rather than either T Tauri stars or EXors (Ábrahám et al. 2004; Andrews et al. 2004).

8. The tremendous wind that occurred soon after the outburst, with velocities upward of 600 km s$^{-1}$ (Reipurth & Aspin 2004a), was very reminiscent of those that were seen in V1057 Cyg, a classical FUor, soon after it erupted in 1969 (G. H. Herbig 1977, private communication).

9. The majority of FUors show signs of an active molecular CO outflow (Evans et al. 1994; Hartmann & Kenyon 1996). This is not the case for V1647 Ori (Lis et al. 1999; Andrews et al. 2004). However, FU Ori itself shows no evidence of having a molecular outflow either (Bally & Lada 1983; Evans et al. 1994). This is also true for the FUor-like close double AR 6A and 6B in NGC 2264 (Aspin & Reipurth 2003; Moriarty-Schieven et al. 2008).
5. CONCLUSIONS

From the data and discussion presented above, it seems clear that V1647 Ori possesses a number of attributes in common with both FUors and EXors. Its similarity to FUors is highlighted by the striking nature of the structure observed in high-resolution NIR spectra, which appears almost identical to that seen in several classical FUors. Its similarity to EXors is highlighted by its outburst timescale and repetitive nature. It is perhaps tempting to place this source in a new, intermediate group. This was recently suggested by Kóspál et al. (2007) and Chochol et al. (2006) where they linked V1647 Ori and the deeply embedded outburst source (DEOS) OO Ser (Hodapp et al. 1996) as prototypes of a new class of eruptive variables. However, rather than creating an ad hoc classification, we prefer to simply conclude that V1647 Ori has characteristics in common with both types of variables. This perhaps suggests that either the FUor or the EXor designations are not as distinct as previously thought or that FUor events need not span many decades as has been found so far. It may also hint at an area of commonality in the mechanisms that trigger both EXor and FUor outbursts. Whichever of the triggering mechanisms discussed in Section 1 is in effect, it is probably going to result in repetitive outbursts (directly observed in EXors). Perhaps some, or all, of the proposed mechanisms may occur, and the one that produced the eruption is dependent on the specific details of the physics and geometry of the young star’s circumstellar environment and its multiplicity state.

As to V1647 Ori itself, the appearance of its 2 \( \mu \)m spectrum at \( R \sim 18 \), 000 suggests that the emitting region is influenced by absorption from both atomic and molecular species and this appears to be the case for all FUors observed. We defer further discussion of the origin and correspondence of high-resolution NIR spectral feature in FUors and EXors to a subsequent paper (C. Aspin et al. 2009, in preparation).

We consider that the idea of the existence of a “continuum” of eruption characteristics is worthy of further investigation. The discovery of more eruptive variables and their relationship to the known FUors and EXors is clearly important as is obtaining high-resolution NIR spectroscopy of more EXors especially during outburst and as the event declines. Such discoveries will be undoubtedly made through large-scale multi-epoch optical surveys such as those soon to be undertaken by Pan-STARRS-1 (Kaiser et al. 2002) and VYSOS (Reipurth et al. 2004).

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