HIGH-RESOLUTION NEAR-INFRARED SPECTROSCOPY OF FUORS AND FUOR-LIKE STARS*

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ABSTRACT

We present new high-resolution (R ≃ 18,000) near-infrared spectroscopic observations of a sample of classical FU Orionis stars (FUors) and other young stars with FUor characteristics that are sources of Herbig–Haro (HH) flows. Spectra are presented for the region λ = 2.203–2.236 μm which is rich in absorption lines sensitive to both effective temperatures and surface gravities of stars. Both FUors and FUor-like stars show numerous broad and weak-unidentified spectral features in this region. Spectra of the 2.280–2.300 μm region are also presented, with the 2.2935 μm ν = 2–0 CO absorption bandhead being clearly the strongest feature seen in the spectra of all FUors and FUor-like stars. A cross-correlation analysis shows that FUor and FUor-like spectra in the 2.203–2.236 μm region are not consistent with late-type dwarfs, giants, nor embedded protostars. The cross-correlations also show that the observed FUor-like HH energy sources have spectra that are substantively similar to those of FUors. Both object groups also have similar near-infrared colors. The large line widths and double-peaked nature of the spectra of the FUor-like stars are consistent with the established accretion disk model for FUors, also consistent with their near-infrared colors. It appears that young stars with FUor-like characteristics may be more common than projected from the relatively few known classical FUors.

Key words: accretion, accretion disks – infrared: stars – stars: formation – stars: pre-main sequence – techniques: spectroscopic

1. INTRODUCTION

FU Orionis stars (FUors) are rare. Classical FUors have been identified by large (~5 mag) increases in brightness and luminosity followed by fading over decades, and only a few young stars have been confirmed as such, notably FU Ori, V1057 Cyg, V1515 Cyg, V1735 Cyg (Herbig 1977), V346 Nor (Graham & Frogel 1985), and V733 Cep (Reipurth et al. 2007). Additionally, while in outburst, they exhibit optical and near-IR spectra similar to FU Orionis itself (Herbig 1977; Hartmann & Kenyon 1996; Herbig et al. 2003). The absorption line widths (interpreted as rotational velocities) and derived spectral types of FUors change with wavelength, varying from F or G in the visible to M type in the near-IR. Their spectra also indicate supergiant or giant surface gravities. These characteristics have been modeled as arising from young stars with massive accretion disks, the latter dominating the spectra and luminosities of these objects (see Hartmann & Kenyon 1996). The accretion disk model has been quite successful in explaining the basic visible-to-IR spectral features and energy distributions of FUors (Hartmann & Kenyon 1985; Kenyon et al. 1988; Hartmann et al. 2004; Green et al. 2006), although in detail there are still discrepancies (Herbig et al. 2003). The only published (and modeled) high-resolution near-IR spectra of FUors have been in the vicinity of the first vibrational overtone ν = 0–2 of CO (λ ≳ 2.294 μm), providing temperature and rotation information. New observations at other near-IR wavelengths may aid in determining the range of effective temperatures and surface gravities over which FUor spectral features arise in the near-IR, providing more constraints on applicable physical models.

The general symmetry and relatively even spacing often seen in Herbig–Haro (HH) object knots strongly suggest that they are somehow linked to episodic outbursts from their parent star plus disk systems (Dopita 1978; Reipurth 1989). This suggests that the sources of HH objects and FUor outbursts may possibly be related. Reipurth & Aspin (1997) found that five young stars associated with HH flows (termed HH energy sources or HHEs) had low-resolution K-band spectra that are very similar to those of FUors. If episodic outbursts do generally indicate FUor activity, then there may be many more young stars with FUor characteristics than the number predicted by extrapolating numbers from the few known classical FUors. In the following discussions, we use the term FUor-like star to indicate objects that have spectral similarities to the classical FUors, but for which no eruption has been witnessed (Reipurth et al. 2002).

How similar are classical FUors and FUor-like stars? Both are young stars that are likely undergoing episodes of high accretion. However, their luminosities may be powered by different physical processes or they may be at different phases of their outburst and decay cycles. It is also important to understand how similar these objects are to embedded (Class I) protostars accreting at fairly high rates (e.g., M ~ 10−6 M⊙ yr−1) and to investigate whether there are any spectral similarities between protostars, FUors, and FUor-like objects. Also, do any of these objects show spectral characteristics similar to other young eruptive variables such as EX Lupi-type (EXors) young stars? EXors undergo multiple short duration optical outbursts of 1–5 mag but have K or M dwarf optical spectra dominated

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by emission lines, much different from FUor spectra (e.g., see Herbig et al. 2001).

We believe that such fundamental questions can be addressed with new high-resolution spectra. Such spectra must cover near-IR wavelengths since many FUor-like stars are highly extinguished and cannot be observed in visible light. The low-resolution near-IR spectra of Reipurth & Aspin (1997) did show strong similarities between FUors and FUor-like objects, but those spectra were also consistent with giant stars. One object with such a near-IR spectrum in close proximity to a young star was recently found to be a background giant star (Aspin & Greene 2007). Linking other young stars to FUors will improve our knowledge of the number and types of young stars with high accretion rates, and detailed modeling may reveal more information on physical structures and accretion mechanisms or processes.

We have conducted a new near-IR spectroscopic study of FUors and FUor-like stars covering a relatively broad range of wavelengths near 2 μm, including spectral features sensitive to both effective temperature and surface gravity. We present these new data in Section 2. The properties of the individual FUor-like stars are discussed in Section 3. In Section 4, we analyze the similarity of the spectra of FUor-like stars to those of (i) classical FUors, (ii) late-type spectral standards, and (iii) Class I protostars. We discuss the likely physical similarities of these stars and the possible origins of their attributes in protostars. We discuss the likely physical similarities of classical FUors, (ii) late-type spectral standards, and (iii) Class I similarity of the spectra of FUor-like stars to those of (i) clas-

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Table 1

| Source | α(2000) | δ(2000) | Observed date | Int. time | S/N | Observatory |
|--------|---------|---------|---------------|-----------|-----|-------------|
| FUor-like HHENs |
| L1551 IRS5 | 04 31 34.1 | +18 08 05 | 2001 Nov 6 | 20.0 | 90 | Keck |
| V883 Ori | 05 38 18.1 | −07 02 27 | 2007 Mar 6 | 1.0 | 140 | Keck |
| Parsamian 21 | 19 29 00.7 | +09 38 39 | 2001 Jul 7 | 33.0 | 220 | Keck |
| HH 381 IRS | 20 58 21.4 | +52 29 27 | 2001 Jul 7 | 21.0 | 190 | Keck |
| HH 354 IRS | 22 06 50.7 | +59 02 49 | 2001 Jul 7 | 21.0 | 60 | Keck |
| FUors |
| FU Ori | 05 45 22.4 | +09 04 12 | 2007 Mar 6 | 1.0 | 120 | Keck |
| V1057 Cyg | 20 58 53.7 | +44 15 29 | 1999 Aug 30b | 13.0 | 300 | IRTF |
| 1996 Sep 2c | 2.0 | 250 | IRTF |

Notes.

a Single-order spectrum of the 2.2194–2.2290 μm region with spectral resolution R ∼ 40,000. This spectrum is not shown in the figures of this paper (as it is largely superseded by the Keck spectra), but it is used in the cross-correlation analysis.

b Spectrum of the 2.29353 μm ν = 0–2 CO bandhead region with spectral bandwidth ∼57 Å.

c Spectrum of the 2.2075 μm Na line region with spectral bandwidth is ∼55 Å. These spectra were originally published in Greene & Lada (2007).

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2. OBSERVATIONS AND DATA REDUCTION

High-resolution near-IR spectra of several classical FUors and FUor-like stars were acquired with the NASA IRTF, Keck II, and GEMINI-South telescopes. The observation dates, total integration times, signal-to-noise, equipment used, and coordinates of all observed objects are given in Table 1.

2.1. Object Sample

The observed FUors and FUor-like objects are listed in Table 1. The FUor-like HH sources V883 Ori, HH 354 IRS, HH 381 IRS, and L1551 IRS 5 were observed by Reipurth & Aspin (1997) who found that their low-resolution (R ∼ 420) K-band spectra were similar to those of FUors. Parsamian 21 has not to our knowledge been observed previously with near-IR spectroscopy. The spectra of L1551 IRS 5 were previously published in Doppmann et al. (2005). New and unique observations were made of the FUor V1057 Cyg in the 2.2935 μm CO bandhead region, and we use its previously published spectrum in the 2.2075 μm Na line region (Greene & Lada 1997). New spectra of FU Ori itself were also acquired.

2.2. IRTF Observations

Near-IR spectra of V1057 Cyg were acquired on UT 1999 August 30 with the 3.0 m NASA Infrared Telescope Facility on Mauna Kea, Hawaii, using the CSHELL facility single-order cryogenic echelle spectrograph (Tokunaga et al. 1990; Greene et al. 1993). Spectra were acquired with a 1′′ (5-pixel) wide slit on the dates indicated in Table 1. This provided a spectroscopic resolution R ≡ λ/δλ = 21,000 (14 km s⁻¹). The spectrograph was fitted with a 256 × 256 pixel InSb detector array, and custom circular variable filters (CVFs) manufactured by Optical Coating Laboratories Incorporated were used for order sorting. These filters successfully eliminated the significant interference fringing normally produced in CSHELL and other echelle spectrographs which use CVFs for order sorting. The plate scale was 0′′20 pixel⁻¹ along the 30′ long slit (oriented east–west on the sky), and all spectra were acquired at a central wavelength setting of 2.29353 μm corresponding to the ν = 2–0 CO bandhead. Each exposure had a spectral range ∆λ ∼ λ/400 (∆v ∼ 700 km s⁻¹).

Data were acquired in pairs of exposures of up to 180 s duration each, with the telescope nodded 10′ east or west between exposures so that object spectra were acquired in all exposures. The total integration time on V1057 Cyg was 13.0 min. The A1V star HR 8585 was observed at nearly identical airmass for telluric corrections. Spectra of the internal CSHELL continuum lamp were taken for flat fields, and exposures of the internal CSHELL Ar and Kr lamps were used for wavelength calibrations.
2.3. Keck Observations

Spectra of FU Ori and all five FUor-like stars were acquired on UT 2001 July 7–8, 2001 November 6, and 2007 March 6. These data were obtained with the 10 m Keck II telescope on Mauna Kea, Hawaii, using the NIRSPEC multi-order cryogenic echelle facility spectrograph (McLean et al. 1998). Spectra were acquired with a 0.58 (4-pixel) wide slit, providing spectroscopic resolution \( R \equiv \lambda / \delta \lambda = 18,000 (16.7 \text{ km s}^{-1}) \). The plate scale was 0.20 pixel\(^{-1}\) along the 12" slit length, and the seeing was typically 0.5–0.6. The NIRSPEC gratings were oriented to allow orders containing the 2.1066 \( \mu \text{m} \) Mg and 2.1099 \( \mu \text{m} \) Al lines, the 2.1661 \( \mu \text{m} \) HI Br \( \gamma \) line, the 2.206 and 2.209 \( \mu \text{m} \) Na lines, and the 2.2935 \( \mu \text{m} \) CO bandhead regions to fall onto the instrument’s 1024 × 1024 pixel InSb detector array. The NIRSPEC-7 blocking filter was used to image these orders on the detector. NIRSPEC was configured to acquire all exposures of more than several seconds duration. Spectra images from the NIRSPEC internal “SCAM” IR camera during all exposures of more than several seconds duration. Spectra of the internal NIRSPEC continuum lamp were taken for flat fields, and exposures of the Ar, Ne, Kr, and Xe lamps were used for wavelength calibrations.

2.4. GEMINI Observations

Spectra of FU Ori were acquired on UT 2006 April 03 with the Phoenix near-IR spectrograph (Hinkle et al. 2002) on the 8 m GEMINI-South telescope on Cerro Pachon, Chile. Spectra were acquired with a 0.35 (4-pixel) wide slit, providing spectroscopic resolution \( R \equiv \lambda / \delta \lambda = 40,000 (7.5 \text{ km s}^{-1}) \). The grating was oriented to observe the spectral range \( \lambda = 2.1914–2.2290 \mu \text{m} \) in a single long-slit spectral order, and a slit position angle of 90° was used. Data were acquired in a pair of exposures of 120 s duration each, with the telescope nodded 6" along the slit between frames so that object spectra were acquired in all exposures. Early-type (B9–A2) dwarfs were observed for telluric correction of the FUor and FUor-like spectra. The telescope was automatically guided with frequent images from the NIRSPEC internal “SCAM” IR camera during all exposures of more than several seconds duration. Spectra of the internal NIRSPEC continuum lamp were taken for flat fields, and exposures of the Ar, Ne, Kr, and Xe lamps were used for wavelength calibrations.

2.5. Data Reduction

All data were reduced with IRAF. First, object and sky frames were differenced and then divided by normalized flat fields. Next, bad pixels were fixed via interpolation, and spectra were extracted with the APALL task. Spectra were wavelength calibrated using low-order fits to lines in the arc lamp exposures, and spectra at each slit position of each object were co-added. Instrumental and atmospheric features were removed by dividing wavelength-calibrated object spectra by spectra of early-type stars observed at similar airmass at each slit position. Final spectra were produced by combining the spectra of both slit positions for each object and then normalizing them so that they had a mean relative flux of 1.0 in each order.

3. NOTES ON INDIVIDUAL FUOR-LIKE OBJECTS

We now discuss what is already known about the individual FUor-like HHENs, with a focus on the properties that indicate episodic variability or other properties that indicate FUor-like behavior.

3.1. L1551 IRS 5

L1551 IRS 5 was discovered in the near-IR survey of the Taurus cloud by Strom et al. (1976). It was found to be associated with a molecular outflow (Snell et al. 1980) and is a close binary system (e.g., Bieging & Cohen 1985). Rodríguez et al. (2003) discovered that both binary components drive aligned ionized bipolar jets from cm wavelength observations. L1551 IRS 5 was confirmed as a FUor-like star by Strom & Strom (1993) after the initial classification by Mundt et al. (1985). It is an IRAS source (04287+1801) with a 12 \( \mu \text{m} \) flux of \( \sim 10 \text{ Jy} \) and was later found to be a triple system with separations 47 and 13 AU (Lim & Takakuwa 2006). It is the driving source of an optical bipolar jet designated HH 154 (Mundt & Fried 1983).

3.2. V883 Ori

This object was first noted as a faint star illuminating an extensive reflection nebula (designated IC 430) on photographic plates dating from 1888. In the H\( \alpha \) emission line survey of Haro (1953), it was described as being faint with some nebulosity and given the designation Haro 13a. Optical spectroscopy of the reflection nebulosity suggested that V883 Ori was a FUor (Strom & Strom 1993). V883 Ori possesses a curving tail of nebulosity, as do many FUors, and is an IRAS source (05358-0704) with a 12 \( \mu \text{m} \) flux of 52 Jy. It has a bolometric luminosity of \( \sim 400 L_\odot \) and sub-mm observations have determined that it has an (unresolved) circumstellar gas+dust mass of \( \sim 0.4 M_\odot \) (Dent et al. 1998). It is thought to be the driving source of HH 183 (Strom et al. 1986).

3.3. Parsamian 21

Parsamian 21 was first noted in the catalog of cometary nebulae by Parsamian (1965). From optical images and spectroscopy, Staude & Neckel (1992) concluded that this source was a possible FUor and discovered a small bipolar HH flow (later labeled as HH 221) emanating from the star. Kospál et al. (2007) found that the H\( \alpha \) knots first observed by Staude & Neckel (1992) were moving at velocities 120–500 km s\(^{-1}\), and their high-resolution near-IR direct and polarimetric images reveal a circumstellar envelope, a polar cavity, and an edge-on disk. Parsamian 21 is associated with a cold IRAS source (19266+0932) with 12 \( \mu \text{m} \) flux of 0.8 Jy and a 100 \( \mu \text{m} \) flux of 15 Jy. Bally & Lada (1983) found no associated CO outflow from the star.

3.4. HH 381 IRS

HH 381 IRS shows prominent optical (Devine et al. 1997) and near-IR nebulosity (Connelley et al. 2007) and is an IRAS source (20658+5217) with a 12 \( \mu \text{m} \) flux of 0.3 Jy and 100 \( \mu \text{m} \) flux of 11 Jy. Devine et al. (1997) also considered it the driving source of the HH objects HH 381/382. HH381-IRS was found to have a near-IR spectrum almost identical to that of L1551 IRS 5 by Reipurth & Aspin (1997). Magakian et al. (2008) found...
that the star and associated nebulosity were very faint on DSS-1 (1953) plates while bright in DSS-2 (1990) images, and even brighter on recent CCD images. Finally, it is not yet conclusive that HH 381 (and in fact HH 380, and 382) originates from HH381-IRS since there are several other IRAS sources in the region.

3.5. HH 354 IRS

HH354-IRS is located in Lynds 1165 and drives a large-scale HH flow covering $\sim$2.4 pc (Reipurth et al. 1997). It is associated with an IRAS source (22051+5848) and has a weak 12 $\mu$m flux of 0.3 Jy and a strong 100 $\mu$m flux of 94 Jy. Its bolometric luminosity is $\sim$120 $L_\odot$. It was found to have a near-IR spectrum very similar to L1551 IRS 5 (Reipurth & Aspin 1997) and possess a strong CO flux suggesting a gas+dust mass of $\sim$30 $M_\odot$ and a CO outflow (Visser et al. 2002).

4. ANALYSIS AND RESULTS

Spectra of the classical FUors V1057 Cyg and FU Ori are shown over the 2.203–2.236 $\mu$m and the 2.280–2.300 $\mu$m ranges in Figure 1. The GEMINI-South spectrum of FU Ori is not shown here because it was superseded by the shown Keck II NIRSPEC spectrum. However, the GEMINI data are used in the subsequent analysis. Figure 1 also shows the spectra of the M4V star GJ 402 (from Doppmann et al. 2005), the M2 lab star $\alpha$ Ori (from Wallace & Hinkle 1996), and the veiled ($r_\lambda = 1.7$) K5–7 Class I protostar $\rho$ Oph IRS 63 (from Doppmann et al. 2005). The spectra of $\alpha$ Ori were smoothed so that the CO bandhead has approximately the same slope as the FUors, requiring an effective broadening of $v \sin i \approx 100$ km s$^{-1}$. The $\alpha$ Ori spectra were also artificially veiled by $r_\lambda = 1.0$ so that their features have depths similar to those found in the FUors and FUor-like stars. The spectra of the five FUor-like HHEns and $\alpha$ Ori are shown in Figure 2.

4.1. Spectral Properties

The M4 V star GJ 402 shows strong neutral atomic absorption lines of Na, Sc, Ti, Fe, and Mg species that are diagnostic of both effective temperature and surface gravity (e.g., see Doppmann et al. 2005). The $v = 2$–0 CO bandhead and redward vibration–rotation lines are also very prominent, and their depths are good indicators of surface gravity when interpreted together with the atomic features. The narrow profiles of all lines (except the somewhat gravity-broadened Na lines) are indicative of slow, unresolved rotation ($v \sin i < 17$ km s$^{-1}$). The Class I protostar IRS 63 has similar features but they are much weaker due to significant near-IR veiling. They are also broad due to the object’s considerable rotational velocity, $v \sin i = 45$ km s$^{-1}$ (Doppmann et al. 2005). The spectra of the M2 lab star $\alpha$ Ori show significant Na, Ti, and CO absorption in addition to many
Spectra of five FUor-like stars and the M2 Iab star α Ori. The spectra of α Ori have been smoothed so that the CO bandhead has approximately the same slope of the FUor-like stars, $v \sin i \approx 100$ km s$^{-1}$.

Optical spectra of FUors have been modeled as being produced in either a circumstellar disk (e.g., Hartmann & Kenyon 1985; Kenyon et al. 1988) or else in a rapidly rotating G-type supergiant atmosphere surrounded by a chromosphere and a cooler absorbing shell (e.g., Petrov & Herbig 1992; Herbig et al. 2003). The near-IR spectrum of FU Ori in the vicinity of the $\Delta v = 2$ CO bandhead and nearby ro-vibration lines has been successfully modeled as arising in a rotating accretion disk at radii where the disk photosphere has an effective temperature and surface gravity characteristic of an M-type giant or supergiant (Kenyon et al. 1988; Hartmann et al. 2004). Figure 1 shows that the larger band-width near-IR spectra of FU Ori and V1057 Cyg do share some similarities with the artificially broadened and veiled spectra of the M2 supergiant α Ori, but overall they appear to be more similar to the spectra of the FUor-like stars in Figure 2. Likewise, the FUor-like stars appear to have spectra more similar to FUors than to rotating, veiled late-type stars or Class I protostars.

4.2. Cross-Correlation Analysis

We now quantify the similarity of the spectra of the FUors and FUor-like stars with those of the stellar dwarfs, stellar giants, and Class I protostars by examining their cross-correlations. Figure 3 shows the cross-correlation functions of the 2.203–2.236 µm spectrum of the FUor-like star HH 381 IRS against template spectra of FU Ori (Keck spectrum), α Ori (M2 Iab), GJ 402 (M4 V), and IRS 63 (late-type protostar). Spectra have been shifted slightly to produce symmetrical cross-correlation peaks at 0 km s$^{-1}$, effectively eliminating relative radial velocities. The high central peak and symmetrical nature of the cross-correlation in the top panel indicates that the spectra of HH 381 IRS and FU Ori have very similar features, but correlations with the giant, dwarf, and embedded protostar are poor.

The broad cross-correlation peaks in all panels of Figure 3 indicate that HH 381 IRS has broad spectral features.
Figure 3. Cross-correlation functions of the 2.203–2.236 μm spectrum of the FUor-like star HH 381 IRS. The high central peak and symmetrical nature of the cross-correlation in the top panel indicates that the spectra of HH 381 IRS and FU Ori have similar features, but correlations with the giant, dwarf, and embedded protostar are poor. Spectra have been shifted slightly in wavelength (and therefore radial velocity) to produce symmetrical cross-correlation peaks at 0 km s\(^{-1}\).

The peak of the cross-correlation with FU Ori has a half width of approximately 100 km s\(^{-1}\), indicating that the 2 μm spectra of these objects are originating from regions rotating with velocities \(v \sin i \sim 70\) km s\(^{-1}\) each (also consistent with the similarly broad line widths seen in Figures 1 and 2). The cross-correlation of HH 381 IRS and the slowly rotating M4 dwarf GJ 402 is double-peaked, consistent with the spectrum of HH 381 IRS originating in a rotating disk (Kenyon et al. 1988; Hartmann et al. 2004). This was also seen in the cross-correlation of HH 381 IRS (and other FUor-like stars) with the slowly rotating M giant HR 5150 (from Doppmann et al. 2005, not shown). The cross-correlations with the other stars do not have double-peaked structures, likely because of their large rotation velocities (natural in IRS 63 and artificially added in \(\alpha\) Ori).

We have computed cross-correlation functions of all FUor-like stars over the 2.203–2.236 μm wavelength interval using FU Ori (Keck spectrum), \(\alpha\) Ori, HR 5150 (M1.5 III), GJ 402, and the protostar IRS 63 as templates. We have computed the Tonry & Davis (1979) \(r\)-values, a measure of the correlation peak height to the average noise, for each correlation function. These values are presented in Table 2, with values greater than 3 indicating a significant correlation.

Table 2 shows that the spectra of the FUor-like HHENs are more strongly correlated with FUor spectra than other stars in every case. Also, all FUor-like stars are significantly correlated with the spectrum of FU Ori itself (\(r > 3\)). The FUor-like stars L1551 IRS 5, Parsamian 21, HH 354 IRS, and V883 Ori also show nearly or marginally significant correlations (\(r \sim 3\)) with one or more other templates, as does FU Ori. This indicates that FUors and FUor-like stars have some spectral features in common with giants, dwarfs, or protostars. However, the much more significant cross-correlations between FU Ori and FUor-like stars indicate that the spectra of these objects are much more similar to each other than to normal stars or embedded protostars.

In Table 3, we compare the cross-correlation results for each FUor or FUor-like star (over 2.203–2.236 μm wavelength) with each other in an attempt to measure the similarities of their spectral features. Each object is listed in both columns and rows, and the cross-correlation values are given for each source against each other source. Table entries which cross-correlate a source against itself list infinity (∞) as the value. This is not the case, however, for FU Ori, where we have cross-correlated the Keck NIRSPEC spectrum taken on UT 2007 March 06 (and used in all other FU Ori cross-correlations) with the Gemini-S Phoenix spectrum taken on UT 2006 April 03.

Inspection of the cross-correlation \(r\)-values shows that the structure in the spectrum of FU Ori correlates extremely well with that of the FUor-like stars. The 2.223 μm H\(_2\) emission line was artificially removed from the spectrum of L1551 IRS 5 before computing its cross-correlations.

### Table 2

| Object      | FU Ori | \(\alpha\) Ori | HR 5150 | GJ 402 | IRS 63 |
|-------------|--------|----------------|---------|--------|--------|
| L1551 IRS 5 | 4.1    | 2.5            | 3.2     | 2.3    | 3.5    |
| V883 Ori    | 28.7   | 4.3            | 4.0     | 3.8    | 3.8    |
| Parsamian 21| 21.6   | 3.1            | 3.2     | 2.9    | 3.1    |
| HH 381 IRS  | 13.3   | 1.6            | 2.5     | 1.7    | 2.3    |
| HH 354 IRS  | 7.5    | 3.0            | 3.0     | 1.9    | 3.3    |
| FU Ori      | ∞      | 3.4            | 2.9     | 3.3    | 3.1    |

Note.

* The 2.223 μm H\(_2\) emission line was artificially removed from the spectrum of L1551 IRS 5 before computing its cross-correlations.
with L1551 IRS 5 (r ~ 5), V883 Ori (r ~ 29), Parsamian 21 (r ~ 22), HH 381 IRS (r ~ 13), and HH 354 IRS (r ~ 8). This implies that all five sources are spectrally very similar to FU Ori. The inter-correlations of these five sources suggests that L1551 IRS 5 is most similar to HH 354 IRS (r ~ 8), V883 Ori is most similar to FU Ori (r ~ 29), Parsamian 21 is most similar to V883 Ori (r ~ 24), HH 381 IRS is most similar to Parsamian 21 (r ~ 22), and HH 354 IRS is most similar to Parsamian 21 (r ~ 10). We also note that all cross-correlation values are above the r = 3 significance threshold indicating that all have significant similarities to all others. The significance of the cross-correlation of the two different FU Ori observations is very high (r = 9.1) but not infinite. The finite nature of this value is most likely due to the limited overlapping spectral range (λ = 2.2194–2.2290 μm) of the two observations of FU Ori with different instrumentation. Imperfectly corrected instrumental differences may have also contributed to reducing the significance of the cross-correlation, and the intrinsic spectrum may have also changed slightly between the two epochs.

4.3. Near-IR Colors

The near-IR J H K colors of FUors and HHENs have not previously been compared directly and these wavelengths encompass our spectra, so we present a near-IR color–color diagram of 15 of these objects in Figure 4 (including those without spectra presented in this paper). The H – K and J – H colors in Figure 4 were all computed from Two Micron All Sky Survey (2MASS) catalog data, and the plot shows that most of the HHENs have colors that are consistent with either reddened classical T Tauri stars (falling along the dashed T Tauri locus) or with reddened normal stars with IR excess; only HH 354 IRS has colors that are clearly inconsistent with IR excess. FU Ori, several FUors, and a few FUor-like stars also have colors consistent with reddened early-type stars (early-type stars are near the origin of the plot). However, early-type stars are ruled out and the color degeneracy is broken by the fact that the FUors and FUor-like objects generally show strong near-IR CO absorptions, consistent with late spectral types typical of T Tauri stars. Therefore, most of the FUors and FUor-like HHENs have near-IR colors consistent with having circumstellar disks. However, the large range of colors makes it difficult to differentiate regular stars, FUors, and T Tauri stars (or protostars) by their colors alone. This color range may be produced by some combination of local scattering produced by different amounts and distributions of circumstellar material as well as different object orientations (i.e., disk/envelope orientations).

5. DISCUSSION

The similarity of the FUor and FUor-like spectra and their significant cross-correlations indicate that the spectral lines of these objects must form in physically similar environments. Reipurth & Aspin (1997) had also postulated this based on similarities of low-resolution near-IR spectra, and the high-resolution data presented in this paper confirm that the FUor-like HHENs are more similar to FUors than dwarfs, giants, supergiants, or embedded protostars.

Given the cross-correlation results, the near-IR spectra of FUor-like stars do not appear to be produced in normal stellar photospheres. The broad cross-correlation peaks indicate rotational velocities v sin i ~ 100 km s⁻¹, much larger than measured for T Tauri stars or even the most rapidly spinning.
embedded protostars (Doppmann et al. 2005; Covey et al. 2006). The cross-correlations with late-type dwarfs and the embedded protostar IRS 63 are also generally poor (low significance), but they are somewhat better with late-type giants and supergiants (Table 2). This suggests that the spectral features of FUor-like stars originate in cool regions with low surface gravities that differ from normal stellar photospheres, and the generally good cross-correlations with FUor spectra reinforce this. The strong CO absorptions of the FUors and FUor-like stars (Figures 1 and 2) indicate relatively low effective temperatures, $T_{\text{eff}} \sim 3500$ K (e.g., Kleinmann & Hall 1986). A giant or supergiant star of that effective temperature would have a radius greater than about 40 $R_\odot$ and a mass of approximately 6 $M_\odot$ or more. Such stars have rotational breakup velocities on the order of 100 km s$^{-1}$. Therefore, the CO strengths and projected rotation velocities of FUor and FUor-like spectra (from cross-correlation and CO bandhead widths; Figures 2 and 3) are consistent with giants rotating at breakup. However, the marginal cross-correlation significance with giants or supergiants (Table 2) indicates that the FUors and FUor-like stars are not likely to be ordinary giants or supergiants.

The combined visible and IR spectra of FUors are reasonably well fit by models of line formation in active circumstellar accretion disks (e.g., Kenyon et al. 1988; Hartmann et al. 2004); the decrease in their line widths (and implied rotational velocities) at longer wavelengths is recognized as perhaps the best evidence of line formation in disks. The double-peaked nature of the cross-correlation of FUors and FUor-like near-IR spectra with those of late-type dwarfs (Figure 3) is also consistent with a disk rotational velocity profile, and the significant near-IR excesses exhibited by most of these objects (e.g., Section 4.3 and Figure 4) are also consistent with hot circumstellar disk material.

If the spectra of FUors and FUor-like HHENs are indeed produced in accretion disks, then why are they not more similar to the spectra of embedded protostars with active disks? Even Class I protostars with large veiling and relatively high accretion rates $\dot{M} \sim 10^{-6} M_\odot$ yr$^{-1}$ do not have FUor-like spectra (see also Greene & Lada 2002; Doppmann et al. 2005). In a circumstellar disk model atmosphere, high accretion rates are needed to induce a temperature gradient with a hot midplane and cooler exterior to produce a spectrum similar to a FUor (e.g., Kenyon et al. 1988). Calvet et al. (1991) found that an irradiated accretion disk model with mass accretion rate of $1.6 \times 10^{-4} M_\odot$ yr$^{-1}$ reproduced the near-IR spectrum of FU Ori well, including its CO and H$_2$O absorptions. This accretion rate is approximately two orders of magnitude higher than that of embedded low-mass protostars such as IRS 63. Greene & Lada (2002) estimated that the mass accretion rate of the embedded protostars YLW 15A was $2.3 \times 10^{-6} M_\odot$ yr$^{-1}$, and the same modeling would produce a very similar (within $\sim 50\%$) value for IRS 63 since the two protostars have virtually identical effective temperatures, near-IR veilings, rotational velocities (Doppmann et al. 2005), and IRAS fluxes. It appears that higher accretion rates are needed to produce luminous disks with absorption features similar to those found in FUors. Future discoveries and observations of weaker FUors with lower accretion rates and more active protostars with higher accretion rates would be valuable in constraining further the accretion rate at which a circumstellar disk develops a strong enough temperature gradient to produce absorption lines that dominate those of the stellar photosphere.

The very high degree of similarity of the FUor-like and FUor spectra (and their good cross-correlations) suggest that FUor activity may be more common than indicated from the small number of known classical FUors alone; more young stars have spectra likely to originate in luminous accretion disks. Taking only the list of 20 classical and FUor-like objects by Abrahám et al. (2004) and adding the two other HH sources found to have FUor-like spectra by Reipurth & Aspin (1997) (HH 381 IRS and HH 354 IRS; also confirmed in this work) yields a sample of 22 objects. Of these, five are widely acknowledged to be bona fide classical FUors due to their observed outbursts and spectral properties (FU Ori, V1057 Cyg, V1515 Cyg, V1735 Cyg, and V346 Nor). Therefore, FUor-like stars may outnumber FUors.

However, FUors are certainly not ubiquitous. Very few FUors or stars with FUor-like spectra are found in regions of clustered star formation such as Tau-Aur, $\rho$ Oph, NGC 1333, IC 346, or the Orion Nebula Cluster. Instead, they are mostly found in regions of low star-formation activity. This implies that either FUors are much less frequent or else have many fewer outburst cycles in high-density regions. One possible explanation is that interactions between stars in clusters could disrupt disks, perhaps eliminating much FUor activity during the Class 0 or Class I protostellar evolutionary phases. Alternatively, FUor events may be triggered by the presence of a companion star (Bonnell & Bastien 1992), in which case a dense cluster environment might accelerate the orbital evolution, causing FUor eruptions in clusters to occur mostly during the Class 0 or Class I stages (Reipurth & Aspin 2004). However, these are certainly not definitive explanations, and the causes of FUor events must be understood better before the inhomogeneity in the distribution of FUors and FUor-like stars can be understood.

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