The Discovery of Two FU Orionis Objects in L1641

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ABSTRACT

We have obtained spectra of the reflection nebulosity illuminated by two heavily embedded IRAS sources in the L1641 molecular cloud, Re 50 and IC 430 (V883 Ori). Examination of these spectra in combination with their other properties indicates that these objects are FU Orionis objects. Our spectrum of L1551 IRS 5 confirms the FU Ori classification made for this star by Mundt et al. (1985).

Subject headings: stars: formation, stars: pre-main sequence, circumstellar matter

1. Introduction

Over the last two decades extensive optical/infrared studies of young optically visible pre-main sequence stars have helped to establish a paradigm for the later stages of the star formation process. To date the properties of their precursors have been inferred largely from photometric measurements. We have begun a program to examine the spectra of heavily embedded pre-main sequence objects by taking advantage of the fortuitous circumstance that some of these objects illuminate reflection nebulae. In Lynds 1641 reflection nebulosity is associated with several of the heavily embedded IRAS sources that have no other optical manifestation. The two objects which exhibit the highest surface brightness nebulosity at R are IC 430 (Haro 13a, V883 Ori, 05358-0704), 19.8 mag/", and Re 50 (05380-0728), 20.8 mag/".

IC 430 appeared in a list of nebulous objects in the Orion region contained in the Hα survey of Haro (1953). While Hα emission was not detected from this object, the morphological similarity to HH objects led Haro to suspect association with a star formation event. A faint star, below Haro’s plate limit, is seen at the tip of the nebula and has since been designated V883 Ori. This

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star was interpreted as an embedded middle B main sequence star by Allen et al. (1975) on the basis of an almost featureless image tube spectrogram in the H\(\alpha\) region, which showed neither H\(\alpha\) emission nor absorption, and on its absolute K magnitude.

Re 50 (Reipurth 1985a) was first discussed by Reipurth and Bally (1986) as the source of a powerful molecular outflow whose associated reflection nebulosity has only recently appeared in the blue lobe of the outflow. Polarization studies (Scarrott & Wolstencroft 1988) and near infrared imaging (Casali 1991) have demonstrated that the nebula is illuminated by the IRAS source.

2. Observations

On the night of 1993 January 26 UT we obtained spectra of Re 50 and IC 430 using the RC Spectrograph on the 4 meter telescope. The slit, of length 5' and width 1.3", was aligned along the highest surface brightness part of the reflection nebulosity, at a position angle of 90° for IC 430, 135° for Re 50 and 45° for L1551 IRS 5. The grating had 316 lines/mm and was centered at 7500Å; the detector was a Tektronics 2048x2048 CCD. This combination allowed useful observations to be made from 5500Å to 9500Å with a spectral resolution of 7Å. Three 1800 sec observations were made of Re 50 and of L1551 IRS5; two 1800 sec observations were made of IC 430. On the night of 1993 January 27 UT we obtained a spectrum of FU Orionis with the same instrumental setup.

The spectra were reduced using the TWODSPEC package within IRAF\(^2\). The two dimensional spectra in the observational coordinate system were transformed to a two dimensional array in linear wavelength and spatial coordinates by making use of the multiplicity of night sky emission lines crossing the spectra and traces of stellar spectra placed at different locations on the slit. This procedure allowed improved sky subtraction to be achieved in regions where the nebular surface brightness was low and long slit lengths were coadded.

3. Discussion

In Figure 1 we show the H\(\alpha\) profiles for Re 50, IC 430, L1551 IRS5, and FU Ori. Re 50 and IC 430 show P Cygni H\(\alpha\) profiles with the blue wings evidencing extreme outflow velocities, extending to 1000 km/s for Re 50. The profile morphology is very similar to that of L1551 IRS 5 which was previously classified as an FU Ori object by Mundt et al. (1985) on the basis of the H\(\alpha\)

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profile and by Carr, Harvey and Lester (1987) on the basis of the infrared CO bands. The spectra in both the red region (5500-7500 Å) and the near-IR region (7700-9200 Å) compare well with that of FU Ori and a G2 Ia supergiant spectrum taken previously with the KPNO echelle and smoothed to our present resolution. The spectra do not compare well with late G main sequence spectra. This is shown in Figure 2 where the normalized spectra in the 5600-6800 Å region are shown. Also shown is the region of the infrared Ca triplet, which behaves differently for each object. While the Ca lines appear in net absorption in the spectrum of FU Ori, Welty et al. (1992) have shown, by subtracting disk photosphere model spectra from the observations of FU Ori and V1057 Cyg that these stars show residual emission in the Ca triplet as well. In Z CMa, another probable FU Ori object (Hartmann et al. 1989), the Ca triplet is strongly in emission. The spectrum of IC 430 shows an emission component to the 8662 Å triplet line while the 8498 Å and 8542 Å lines show no evidence for emission. The spectrum of IRS 5 shows a similar phenomenon where the 8662 Å line is seen in emission and the two shorter wavelength lines are not seen, although the higher noise level from the OH emission in the early evening night sky makes the result of low significance for the 8498 Å line. A discussion of the Ca infrared triplet anomaly in pre-main sequence stars can be found in Hamann & Persson (1992). It is difficult to place these objects within that context since the emission components are relatively weak; models would have to be matched to these spectra and subtracted before a true measure of the emission in each line could be given, something best done with higher resolution spectra. Based primarily on the Hα profile and apparent low surface gravity and secondarily on the Ca infrared triplet, we conclude that Re 50 and IC 430 show many of the spectral characteristics similar to those of FU Ori objects.

The characteristics that are used to define an FU Ori object have evolved with time. The first identifications were centered on the observation of a sudden large rise in luminosity over a short period of time. This allowed 3 objects, FU Ori, V1057 Cyg, and V1735 Cyg (Elias 1-12) to be placed in this group. V1515 Cyg is also included although it has exhibited a slow rise lasting many decades. It has been recognized however that this phenomenon is characteristic of very early stages in a star’s evolution, and is probably associated with multiply occurring sudden mass accretion events (Herbig 1977). Recent theoretical work (Hartmann, Kenyon & Hartigan 1993 and references therein) has modeled the FU Ori phenomenon as a sudden increase in the mass accretion rate through a circumstellar accretion disk and has made predictions of spectral features, particularly the 2.3 μm CO absorption bands, and line profile doubling to be expected for the disk model.

Because it is not possible to obtain optical spectra of the resolution necessary to search for line doubling, and we have not yet obtained near infrared spectra, are there other consistency tests that can be applied? 1)In images of FU Ori objects, small actuate nebulosities are apparent (Goodrich 1987). The reflection nebulosity for both Re 50 and IC 430 is typical of the form found for FU Ori objects. 2) While the photometric measurements of V883 Ori are few (2), they are separated by 11 years (Allen et al. 1975, Nakajima et al. 1986), and offer the possibility of detecting a long term decline in the brightness of V883 Ori. In this time period, the object
declined by 0.58 mag at J, 0.57 mag at H, 0.14 mag at K and 0.07 mag at L. Further photometric monitoring will allow us to confirm the decline of this object. 3) The bolometric luminosities of the known FU Ori objects range from $\sim 40L_\odot$ (L1551 IRS5) to $\sim 3000L_\odot$ (Z CMa), (Rodriguez et al. 1990; Hartmann et al. 1989), although $\sim \frac{1}{2}$ of the luminosity of Z CMa may be attributable to its infrared companion. The bolometric luminosity of Re 50 is $\sim 300L_\odot$ while that for IC 430 is $\sim 400L_\odot$. While these are the two most luminous IRAS sources in L1641, they were separated from the rest of the high luminosity embedded sources by Strom et al. (1989) because they did not possess steep red spectral energy distributions. Instead their spectral energy distributions were relatively flat. These spectral energy distributions are more characteristic of the FU Ori objects. 4) The previously classified FU Ori objects (11 objects, Kenyon et al. 1993) show optically thin mm continuum emission which measures the mass of cold dust in the immediate environment of the object (Weintraub, Sandell, & Duncan 1989, 1991; Reipurth et al. 1993) and predominantly located in a structure with small covering angle, therefore allowing the objects to be seen. Both Re 50 and IC 430 have been measured at 1300$\mu$m by Reipurth et al. (1993). The deduced masses for the circumstellar gas and dust immediately surrounding these objects are 3.7 $M_\odot$ for IC 430 and 1.8 $M_\odot$ for Re 50, well above the masses deduced for most of the optically visible FU Ori objects but on the low end of the mass distribution for those objects known to be driving outflows delineated by HH objects. 5) Several FU Ori objects show cm radio emission with a spectral index characteristic of ionized outflows (Rodriguez, Hartmann & Chavira 1990, Rodriguez & Hartmann 1992) Both IC 430 and Re 50 were observed in the VLA snapshot survey of Morgan, Snell and Strom (1990) at 6 cm. Re 50 was clearly detected and the spectral index demonstrated the emission to be thermal. IC 430 was not detected, but the $3\sigma$ noise level is consistent with the range of flux levels measured for FU Ori objects. 6) Several of these objects are also apparently exciting sources of HH objects (L1551 IRS5, HH28,29 (Stocke et al. 1988); V346 Nor, HH57 (Reipurth 1985b)), and long narrow jets (Z CMa, Poetzel et al. 1989) indicative of the energetic outflows diagnosed by the H$\alpha$ profiles. Both of these objects are also associated with HH objects, HH 65 (Reipurth 1989) with Re 50 and a small emission knot with IC 430 (Strom et al. 1986). 7) Approximately half of the FU Ori objects are known to drive molecular outflows (see the summary table in Hartmann, Kenyon and Hartigan 1993). The outflow associated with Re 50 has been well documented (Bally & Reipurth 1986, Fukui et al. 1986) and its interaction with the surrounding cloud material (Casali 1991; Scarrott & Wolstencroft 1988) has been described. However, a molecular outflow has not been found to be associated with IC 430 although a search for such evidence has been conducted (Morgan, Schloerb, Snell & Bally 1991). Neither is there a CS core associated with this object (Tatematsu et al. 1993) although other outflow sources in the cloud are embedded in such cores. However, there is other evidence that an energetic outflow however variable the rate, may have been present in the past. The $^{13}$CO map of the L1641 molecular cloud (Bally et al. 1987) shows an elliptical depression in the molecular gas distribution, centered on this object. The semi-major axis of this cavity is $\sim 0.9$ parsecs. The presence of this cavity is also clearly indicated in our 100$\mu$m IRAS HIRES image of the region. The piled up material at the edges of the cavity emits strongly at 100$\mu$m.
The presence of this object in the Index Catalog is curious in itself since the surface brightness of the nebulosity is so low. Therefore we traced the origin of its listing to a paper by Pickering (1890). This object is described as a nebulous band 3′ wide extending 10′ north preceding from DM-7° 1142. It is possible now to see nebulosity of this description on R and I band CCD images, although we know that the bright star is not responsible for its illumination. However the surface brightness is only ∼20 mag/′′ on our R band CCD image. The photographic plates of that period were sensitive only in the blue. On our B band CCD image taken 1990 Nov 9 UT, it is very difficult to see the nebulosity. The maximum surface brightness near V883 Ori is 24 mag/′′ on this image. It is unlikely that nebulosity of this surface brightness was apparent on the plates taken in 1888. Therefore it is probable that V883 Ori was considerably brighter at that time, and that the epoch of most recent outburst for this object can be placed in or before 1888, when the two discovery plates were taken. The total length of this nebulosity, as measured from V883 Ori, is ∼1 pc, in close agreement with the size of the cleared region of the cloud as seen in 13CO and 100μm images.

4. Conclusions

Spectra of two heavily embedded IRAS sources in L1641 reveal them to have characteristics of FU Ori objects. The other properties of these objects (morphology, bolometric luminosities and spectral energy distributions, HH objects, inferred disk masses, thermal radio emission, and molecular outflow) strengthen the conclusion that they belong to this class. The infrared CO bands should be observed to confirm these identifications. The presence of two FU Ori objects within 1/2 degree of each other in this cloud emphasizes the active star formation occurring in this cloud at the present time.

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Fig. 1.— The Hα profiles for FU Ori, IC 430, Re 50 and IRS 5 are shown on a velocity scale. The P Cygni profiles show little or no emission above the continuum and blue wings to the absorption components extending to large outflow velocities.
Fig. 2.— Spectra for the FU Orionis objects as well as for a supergiant and main sequence comparison star. The regions where background emission lines ([O I] and [S II]) have either been incompletely or over subtracted are marked for IRS 5 and Re 50. The spectra resemble the supergiant standard and FU Ori more closely than the main sequence star. The Ca triplet behavior is quite varied, as discussed in the text.