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OPTICAL SPECTROSCOPY OF HH–EXCITING STARS FROM SCATTERED LIGHT CONTINUA

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ABSTRACT

We present optical spectra of the reflected light continua visible in parts of several Herbig-Haro objects. HH 100 unmistakably scatters the chromospheric spectrum of a strong emission-line T Tau star. HH 48S also reflects a T Tau stellar spectrum, as perhaps do HH 24 and HH 55, but less convincingly. HH 55 reveals photospheric absorption features too, corresponding to an M3.5 T Tau star. The continuum in HH 120 (= CG 30 HH) is unclassifiable while that in HH 46A has dimmed considerably (by a factor of order 20) although, only 7 yr ago, it clearly reflected a strong-line T Tau spectrum. We conclude that at least some of the stars that excite Herbig-Haro nebulae, even when those stars are not directly visible, pass through a strong-line T Tau phase and can undergo abrupt and dramatic changes in visual luminosity.

Subject headings: nebulae: general — stars: pre-main-sequence

I. INTRODUCTION

The nature of the exciting stars of Herbig-Haro (HH) objects remains an intriguing puzzle. Some are visible T Tau stars, with strong, emission-line spectra, photospherically unclassifiable (e.g., DG Tau, AS 353A). Occasionally one is observed in a weak-lined phase, when it is classifiable, e.g., HL Tau, of type K7 (Cohen and Kuhi 1979). Usually, exciting stars are invisible and must be observed in scattered light, seen in some HH nebulae. A blue nebular continuum in HH objects is attributed to enhanced two-photon emission (Dopita, Binette, and Schwartz 1982). Reflected stellar continua are red, showing significant optical polarization, with electric vectors that implicate displaced infrared sources or visible stars (Strom, Strom, and Kinman 1974; Schmidt and Miller 1979; Cohen and Schmidt 1981).

These continua are often too faint for nebular spectropolarimetry. Chromospheric lines of Fe II, common in T Tau stars, may be used to assign an HH–exciting star to this class. The strong, polarized stellar spectrum in HH 30 is a good example where Fe II multiplet 42 is clearly seen (Cohen and Schmidt 1981). Likewise, Dopita (1978) found a strong-line T Tau spectrum in HH 46A. Not all reflected continua are T Tau–like. A possible photospheric absorption led Mundt *et al.* (1985) to suggest that L1551 IRS 5 is an FU Ori star. The exciting star of HH 57 (Graham and Frogel 1985) also has been assigned to this class (Reipurth 1985; Cohen, Dopita, and Schwartz 1986).

The infrared properties of optically invisible HH–exciting stars yield bolometric luminosities, but these alone cannot locate the stars in the H-R diagram. There is no substitute for optical spectroscopy. It is, therefore, critical to obtain spectra of the scattered starlight in HH nebulae.

The events that produce rapidly moving HH knots may be transient. The exciting stars could have evolved appreciably between the present time and the epoch of their last HH–forming activity. The greater the spatial separation between star and HH object, the older the star and the less likely we are to see it in an "eruptive" phase. So it is important to study potentially younger stars, still creating HH knots and little displaced from their most recently formed HH objects.

In this *Letter* we describe optical spectroscopy of several HH knots in which we see a presumed stellar continuum. We have clearly identified a strong emission-line T Tau stellar spectrum in HH 100; can classify the exciting star of HH 55 as an M3.5 type T Tau object; have found a profound change in the brightness of the T Tau starlight reflected by HH 46A; and have studied the continua in HH 24, HH 120 (= CG30 HH), and HH 48S. In all but HH 120 we may see a T Tau chromospheric spectrum.

II. THE OBSERVATIONS

We obtained long-slit spectra of all southern hemisphere HH objects during three nights (1984 Mar 27, Apr 2 and 3) on the Anglo-Australian 3.9 m telescope. We used the IPCS (Boksenberg 1972) with the 25 cm camera and 250 line mm^{-1} grating for coverage from 3500 to 7500 Å, with resolution about 10 Å. The slit was 115″ long and 2″.6 wide, with 50 equal spatial elements along the slit. Details of our reductions are given by Dopita *et al.* (1984).

III. DISCUSSION

a) *HH 100*

Little of the intricate HH 100 nebula (Strom, Strom, and Grasdalen 1974) shows emission lines though portions are HH in character. In several slit positions across the reversed C-shaped head of the nebula we see a strong nonnebular continuum. Figure 1 is the sum of the independent spectra of all pixels with a continuum, minimally contaminated by nebular lines. There is no mistaking the rich, powerful chromospheric spectrum of an underlying T Tau star without photospheric absorption features.

We identify this star with HH 100 IRS (Strom, Strom, and Grasdalen 1974), an HH–exciting star, because of its proximity to HH 100; the parabolic nebula with HH 100 IRS at the apex; the alignments of HH 99A/B, HH 104A/B, and the proper motion vector of HH 104A (Schwartz, Jones, and Sirk 1984) with HH 100 IRS; the recent recognition of jetlike flows from both R and T CrA, none of which is aligned with any of the HH nebulae in this region (Ward-Thompson *et al.* 1985). HH 100 IRS has exhibited irregular infrared variability too (Reipurth and Wamsteker 1983).

b) *HH 24*

Spectropolarimetry of HH 24A (Schmidt and Miller 1979) established the validity of both "*in situ* shock wave" and "reflected starlight" hypotheses for HH objects. These authors' spectrum of HH 24E (Strom, Strom, and Grasdalen 1974) showed a continuous spectrum, lacking HH lines. Our spectrum confirms this red continuum and suggests the presence of Fe II multiplet 42 (4924, 5018, 5169 Å) and of the stronger lines of multiplet 49 (5198, 5276, and 5317 Å) in emission. To enhance the signal-to-noise ratio we added our spectra of HH 24E and of all other pixels along our slit with a red continuum. Figure 2 shows this combined spectrum, emphasizing the critical region near Hβ. Nebular lines contaminate this spectrum, e.g., [N I] 5200 Å, but the Fe II lines seem clearer than in HH 24E alone. Ca II H and K, and He I 5876 Å are in emission, typical of strong-line T Tau stars. The Ca II lines can arise in shocks, but if they rival or exceed Hγ, a chromospheric component must be invoked. In HH 24, the K line exceeds the H line, and both are more powerful than Hγ. This reflected continuum, therefore, suggests a T Tau star.

Molecular flows in this region are ambiguous as to origins (Snell and Edwards 1982). However, the identification of this embedded object as an HH–exciting star rests on the following: alignments within HH 24 (Cohen and Schwartz 1983); the radio detection of HH 24 IRS (Bieging, Cohen, and Schwartz 1984); and unpublished proper motions for HH 19–27 (Jones 1985).

c) *HH 48S*

Schwartz's (1977) chart for HH 48 shows a double object in p.a. 43°. Both objects show stellar spectra. However, HH 48N shows no emission lines while HH 48S does (Fig. 3). HH 48S has a red continuum without absorption features but Fe II 42 seems to be in emission, and Ca II H and K are enhanced relative to the hydrogen lines. The coincidence of an infrared source with HH 48 (Elias 1980) suggests that this star excites the HH object.

d) *HH 55*

HH 55 lies 3′ from RU Lup, but there is no reason to associate them. Figure 4 shows a conspicuous HH spectrum, superposed on an obvious continuum. Krautter, Reipurth,

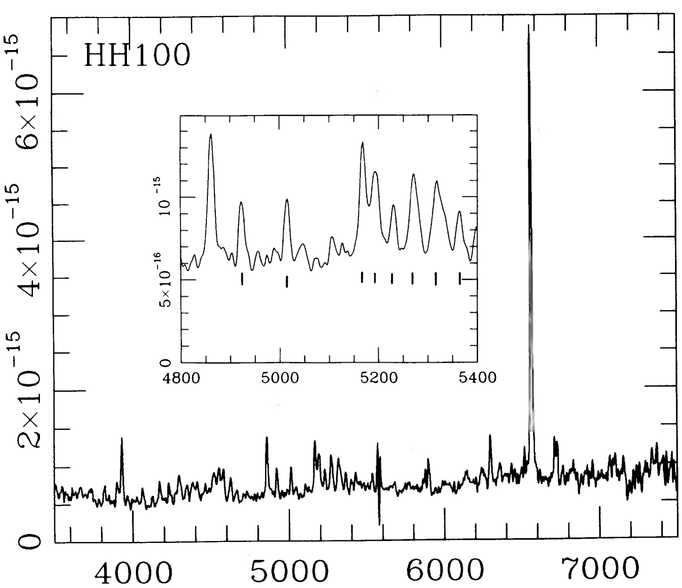

FIG. 1

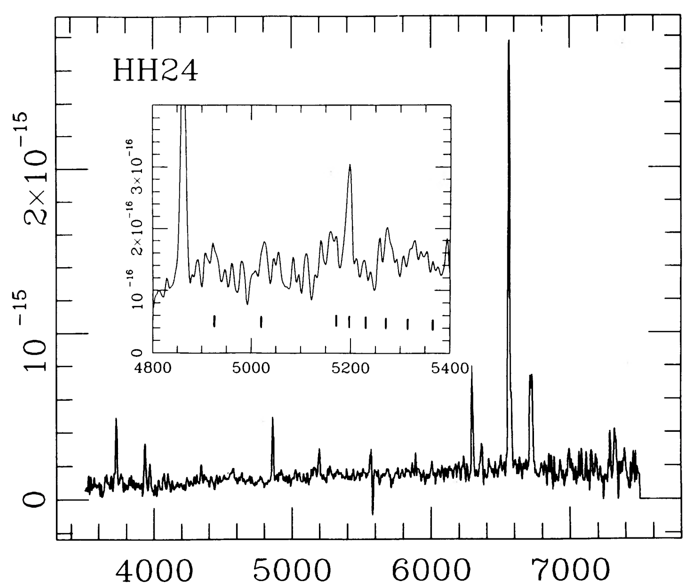

FIG. 2

FIG. 1.—Spectrum of the continuum component of HH 100. Ordinate is F_λ in units of ergs cm^{-2} s^{-1} Å^{-1}. Inset shows the region around Hβ where the most prominent Fe II multiplets appear in T Tau chromospheres. Marks in the inset show the locations of the strongest chromospheric Fe II lines from the HH 100 spectrum.

FIG. 2.—Spectrum of the continuum component in HH 24, as in Fig. 1. Sharp line at 5200 Å is principally due to nebular [N I].

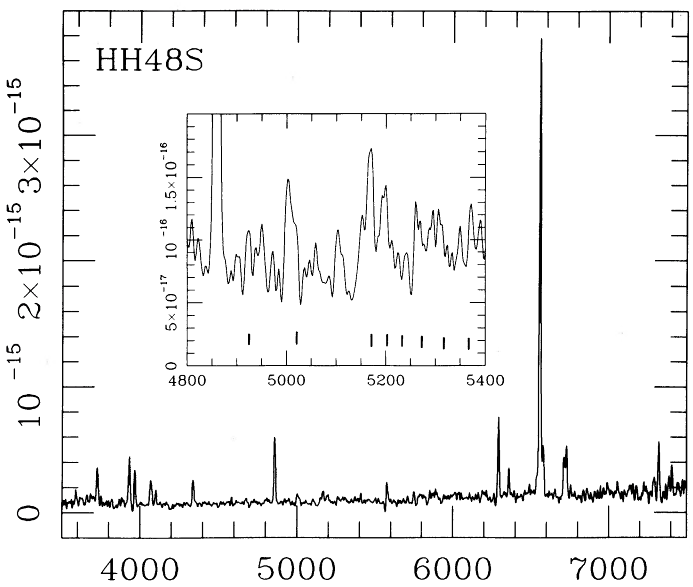

FIG. 3

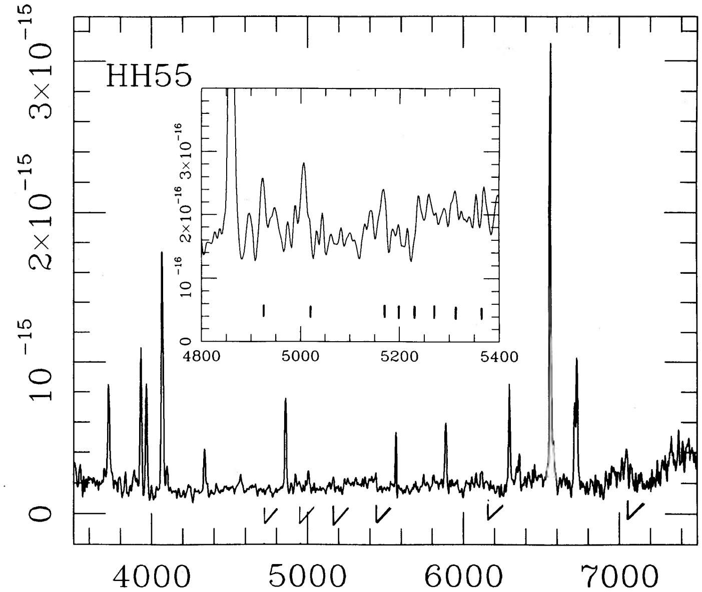

FIG. 4

FIG. 3.—Spectrum of the continuum in HH 48S, as in Fig. 1

FIG. 4.—Spectrum of the continuum in HH 55. Note the very obvious TiO bandheads in the red (the expected positions of commonly seen bandheads are indicated by V's below the spectrum). Details as in Fig. 1.

and Eichendorf (1984) presented a spectrum of HH 55 from 5700 to 6800 Å. They, too, noted strong He I or Na I emission but their signal-to-noise ratio did not yield continuum features. Our longer redward limit and higher quality spectrum enable us to recognize the triplet (0, 0) bandhead of the TiO gamma system near 7054 Å in absorption and explain the curious discontinuity in the spectrum at 5435 Å and depression near 6159 Å. Emission lines of Fe II 42, enhanced emission of Ca II H and K, and the strengths of the TiO bandheads (5435, 6159, and 7054 Å) show the continuum to be from an active T Tau star, of photospheric type M3.5. This excludes RU Lup, which has no recognizable photospheric features, as the exciting star of HH 55.

e) *Is* Fe II *Really Present in HH 24, HH 48S, and HH 55?*

The individual continua in HH 48S, HH 24, and HH 55 are quite evident but the pattern of Fe II lines so characteristic of T Tau chromospheres is not. Figure 5, therefore, presents the sum of the continua reflected by HH 24 (Fig. 2), HH 48S (Fig. 3), and HH 55 (Fig. 4), all of comparable intensity. Figure 5 is strikingly similar to the spectrum reflected by HH 100 (Fig. 1), although potential Fe II lines are weaker. We have tried to verify their existence by cross-correlating this composite spectrum and the individual spectra with that of HH 100, and all of our spectra with a synthetic Fe II spectrum mimicking a strong-line T Tau chromosphere. The region between 4500 and 5500 Å, rich in Fe II lines, was used. Spurious effects of strong nebular lines were avoided by using an interpolated continuum for 40 Å about Hβ and 20 Å about [N I]. Different spectra were rescaled so possible Fe II features had the same strength. Cross-correlation sums were created in one channel steps (2 Å) between reference and object spectra, with shifts up to 40 Å. As control we tested HH 120's spectrum (see below), in which we suspect no Fe II

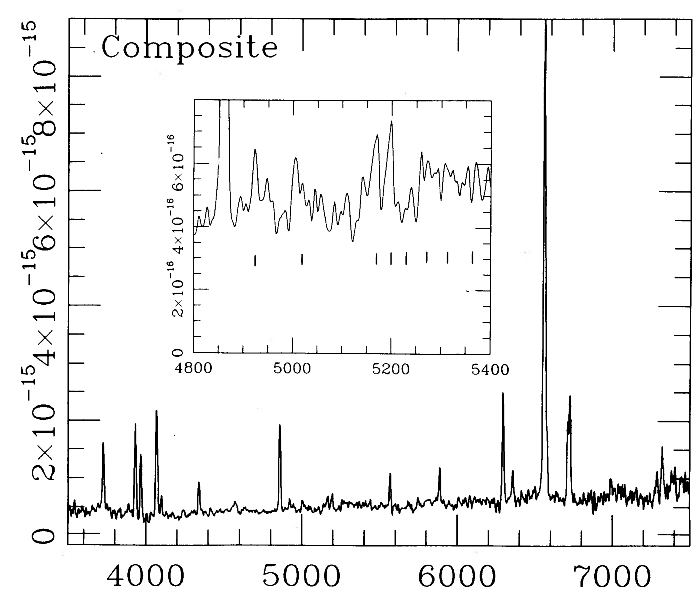

FIG. 5.—Composite spectrum made by adding together those of HH 24, HH 48S, and HH 55. Compare this figure with Fig. 1.

is present, and those of other non–T Tau stars observed on the same nights.

Based upon the zero relative channel shifts of maximum cross-correlation sums, and the enhancements of these sums compared with their values for incorrectly registered spectra, we clearly see Fe II in HH 100, HH 48S, and the composite spectrum. We patently see no Fe II in HH 120, nor in our other controls. HH 24 and HH 55 show weak enhancements in the sums and are best matched for shifts of 4 and −4 Å, respectively. These shifts lie within our spectral resolution but

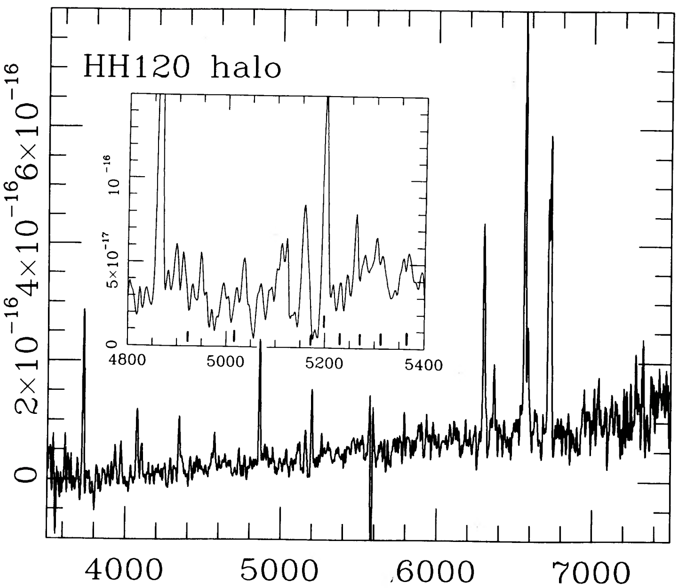

FIG. 6.—Spectrum of the halo of HH 120 showing the red continuum as in Fig. 1.

we conclude that neither HH 24 nor HH 55 offers convincing evidence for Fe II by itself. The correlation is better for the composite spectrum than for HH 48S alone, suggesting that even HH 24 and HH 55 may actually have Fe II.

f) *HH 120* (*CG 30 HH*)

Petterson (1984) has described observations of the HH nebula (Object 2, Reipurth 1981) in CG 30 in great detail. Our own spectra of HH 120 show a red continuum in the "halo" of fainter nebulosity that surrounds the bright core of HH 120 (Fig. 6), and a weaker bluer one in the core itself. However, we find no evidence for emission lines of a T Tau star nor photospheric absorptions of a cool star (e.g., the TiO head at 6159 Å that Petterson described). No strong Fe II multiplets near 5000 Å, nor between 6100 and 6300 Å, are seen nor are the Ca II blue lines enhanced. This impression is quantified by the cross-correlation test described above. The association of this continuum with the exciting star of HH 120 rests solely on the brightness and location of Petterson's source, IRS 3, within the nebula.

g) *HH 46A*

Dopita (1978) observed a relatively bright, rich T Tau emission-line spectrum in HH 46A. Our spectrum of HH 46A, from the sum of six independent night and slit settings, does not show the lines of Fe II so prominent in Dopita's earlier spectrum. We do see a continuum but its brightness has diminished considerably since 1977. The line-peak-to-continuum ratios of the strong red, purely nebular, lines in Dopita's and in our spectrum indicate that the continuum has dropped by a factor of 20. Directly, Dopita's estimate of *V* for this knot, compared with ours, implies that it was 16 times brighter in 1977 than in 1984.

IV. CONCLUSIONS

We conclude that probably all these HH objects (except HH 120) are illuminated by strong-line T Tau stars that are capable of dramatic changes in brightness in relatively short periods, epitomized by the optical behavior of HH 46A and the infrared variations of HH 100 IRS. One might expect that very young stars, still in their accretion phase, could suffer strong luminosity variations due to either erratic mass inflow, or fluctuating circumstellar obscuration in occultations by close-in giant dusty protoplanets, or even intrinsic changes in surface brightness in response to the onset of deuterium burning in their cores (Stahler, Shu, and Taam 1980).

Finally, how do we reconcile the two kinds of star associated with HH objects? Eleven are strong emission-line T Tau stars, five visible directly (DG Tau, HL Tau, R Mon, AS 353A, Th 28), and six by reflection (Haro 6–10, HH 24, HH 30, HH 48S, HH 55, HH 100; HH 46 in 1977 was another). Two are potential FU Ori stars: L1551 IRS 5 (type G–K: Mundt *et al.* 1985) and HH 57's star (F8 III: Cohen, Dopita, and Schwartz 1986). All are clearly unusual stars. Herbig (1977) thought FU Ori-type outbursts might recur in "normal" T Tau stars. Recurrence might apply to HH–exciting stars if, on average, they spent about 5 times as long in their strong-line T Tau, as in their FU Ori, guise. However, the FU Ori phase of L1551 IRS 5 and the HH 57 star could be a very early single event followed by the strong-line phase. We feel that a unique transient event is a serious possibility but, to test for recurrence, we strongly urge that HH 46A be monitored in case it develops P Cyg structure at Hα or photospheric absorptions after its recent strong-line episode.

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