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AN INFRARED SOURCE ASSOCIATED WITH A HERBIG-HARO OBJECT

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ABSTRACT

An infrared source of angular extent $\leq 6''$ has been found associated with a Herbig-Haro object in the Corona Austrina dark cloud. The infrared spectrum of this object, between 5 and 12.6 μ, is very similar to that characterizing three irregular variables of the Orion population located within the same dark cloud. It is proposed that the optical manifestation of this Herbig-Haro object represents the light scattered from a T Tauri–like star embedded deep within the CrA dark cloud.

Subject headings: infrared sources — nebulae — pre–main-sequence stars

I. INTRODUCTION

This contribution reports the detection of an infrared source associated with a Herbig-Haro object located in the Corona Austrina (CrA) dark cloud complex. This discovery appears to offer some important clues toward the solution of two major puzzles presented by these objects: (*a*) their current physical state and source of excitation, and (*b*) their evolutionary status.

The few Herbig-Haro objects thus far described in the literature share the following characteristics:

1) All known Herbig-Haro (H-H) objects have been found within the boundaries of dark clouds, frequently those already known to contain emission-line stars of the "Orion population."

2) The objects appear "semistellar" on small-scale surveys. This criterion is a rather weak one since the objects thus far reported by Herbig range from the almost stellar-like knots near V380 Orionis, published in the initial discovery papers (Herbig 1951; Haro 1952) to the rather diffuse, clumpy structures near M78 (Herbig and Kuhi 1963). No star has yet been found associated with these objects, although careful attempts have been made to search for stars in or near the Herbig-Haro objects (Haro 1952; Mendoza 1969).

3) The forbidden lines of O I at 6300 and 6363 Å and S II features at 4068, 4076, 6717, and 6731 Å are unusually strong, while the weaker emission lines of easily ionized elements are also present (Böhm 1956 and references therein). A weak continuum is also observed in some of the objects. These characteristics are, perhaps prophetically, similar to those found in the small nebulous regions near the T Tauri stars HL Tau (Herbig 1968) and T Tau itself.

4) In a study covering nearly two decades, Herbig has found variations of several magnitudes for the individual bright knots which constitute the object H-H 2 near V380 Ori. The structure of each knot is preserved even though variation of each feature on a time scale of years is suggested. Because the data in the literature are quite sparse, it is not known to what degree irregular variability characterizes all these objects.

The first of the above listed properties forces one to accept the belief that these objects represent a phenomenon associated with the early phases of stellar evolution. A consistent assumption in previous discussions of H-H objects has been to identify them directly with the ionized regions producing the emission line spectrum. This uniformity of interpretation has not led to a standard picture of the role of Herbig-Haro objects in pre–main-sequence evolution. The central question is whether these objects represent a separate phase in the evolution of a protostar presumably prior to the formation of a condensed object or whether they are a phenomenon associated with an already condensed object either hidden within the dark cloud or intrinsically very faint.

Herbig (1969) has suggested that the Herbig-Haro objects represent the envelopes surrounding stars undergoing or about to undergo a rapid rise in brightness similar to that experienced by FU Ori. This explanation was offered primarily to provide the source for the sudden increases in brightness observed in some of the knots in H-H 2. It would appear to be ruled out by the observed behavior of V1057 Cygni, a young star which very recently exhibited a rise in brightness similar to FU Ori. The preoutburst observations of this object clearly identify the parent object of the FU Ori phenomenon as a T Tauri star and not a Herbig-Haro object (Welin 1971).

In order to explain the excitation of the Herbig-Haro objects, Böhm (1956), Osterbrock (1958), and Magnan and Schatzman (1965) have postulated an unknown source of either ionizing photons or energetic particles embedded within the dark cloud.

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TABLE 1

OBSERVED INFRARED MAGNITUDES FOR THE CORONA AUSTRINA HERBIG-HARO OBJECT

[1.25 μ]	[1.6 μ]	[2.2 μ]	[3.5 μ]	[5.0 μ]	[8.4 μ]	[11.2 μ]	[12.6 μ]
> 12.0	10.2	6.8	4.5	3.0	1.5	0.6	0.2

The observation most suggestive that the Herbig-Haro objects are associated with already condensed objects is the close similarity of the spectra of the nebulae near T Tau (Herbig 1950) and HL Tau (Herbig 1968) to those of bona fide Herbig-Haro objects.

The evolutionary interpretation of the Herbig-Haro objects hinges on the presence or absence of a young star or protostellar object near the Herbig-Haro object. Because such an object might be obscured heavily by dark cloud or circumstellar material, our efforts have been concentrated toward observing these objects in the infrared.

II. THE OBSERVATIONS

As part of a larger program of infrared observations of T associations, we have already observed several objects in the dark cloud region surrounding the irregular emission-line variable, R CrA. Examination of the *Palomar Sky Survey* plate near this star revealed a bright nebulous object morphologically similar to known Herbig-Haro objects. We reproduce in figure 1*a* (plate 1) a photograph of this object obtained with the Michigan Curtis-Schmidt telescope located at the Cerro Tololo Inter-American Observatory; an 098-02 emulsion and a Schott RG-1 filter were combined to yield a deep, red exposure covering the wavelength band 6100–7200 Å. The presumably more optically thin parts of the dark cloud appear luminous, although devoid of stars, on a deep exposure. The bright nebulous object is clearly associated with the region which appears to be the darkest part of the CrA complex. We interpret this dark concentration as a region of very high density, a view which seems borne out by our later discussion.

Figure 1*b* is a photograph of this region obtained with a 90-mm, S-20 ITT image intensifier at the f/13.5 focus of the Kitt Peak National Observatory 36-inch (91-cm) telescope and filtered to respond to wavelengths in the range 7000–8200 Å. Even with the relatively large plate scale (16″.7 mm^{-1}) and long effective wavelength of this photograph, no stellar condensations were found either within the apparent Herbig-Haro object or within the dark concentration.

A spectrum of this object was taken at a dispersion of 240 Å mm^{-1} at the KPNO 84-inch (213-cm) tele-

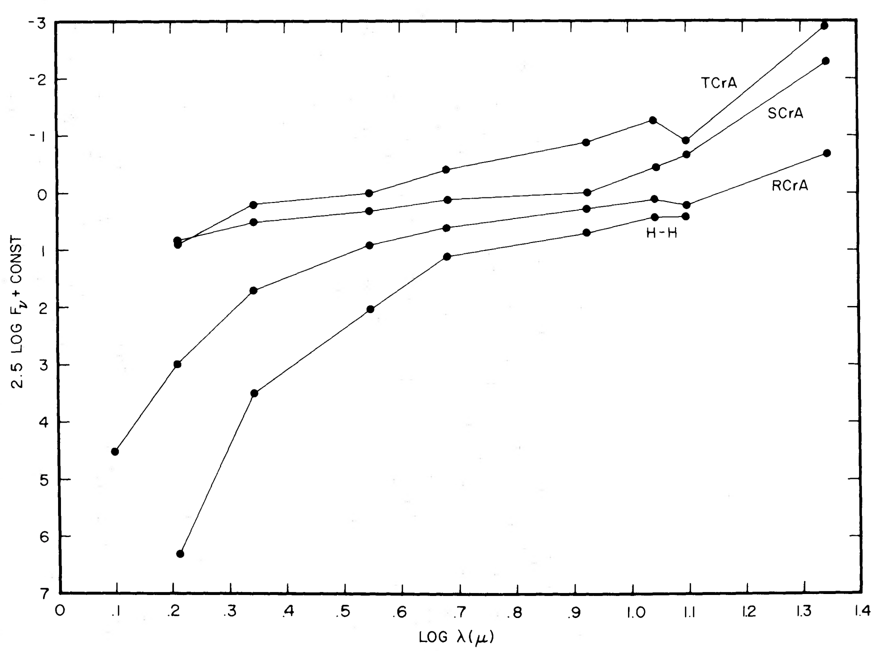

FIG. 3.—The infrared spectral energy distributions measured for the Herbig-Haro object and for R, S, and T CrA, three variables of the Orion population associated with the CrA dark cloud complex.

scope with the Lynds image-tube spectrograph and is reproduced in figure 2 (plate 2). The unfavorable declination of this object and associated technical difficulties with the spectrograph prevented our obtaining a first-class spectrogram. Despite these problems, the plate reveals a strong Hα emission feature and a comparably strong blend of the [S II] lines at 6717 and 6731 Å. A weak continuum is also present. The strength of the atmospheric [O I] emission at 6300 Å precludes any statement regarding the presence or absence of this feature in the object. Nevertheless, the morphological similarity to other Herbig-Haro objects, the unusual strength of the [S II] feature, and its association with the CrA dark cloud complex make us quite certain of this object's identification as a Herbig-Haro object.

Infrared observations of this object were first obtained at the KPNO 50-inch (1.3-m) telescope with the Dyck PbS photometer used with a 35″ beam. The choice of this beam size in our initial search was fortunate since the infrared source is displaced from the apparent center of the optical object, as shown in figure 1*a*. Subsequent observations of this object with the Dyck bolometer system (beam size 12″) allowed us to determine its location as $\alpha(1950) = 18^h58^m28^s.3 \pm 0^s.5$, $\delta(1950) = -37°02'27'' \pm 7''$. Scans in declination suggest that the object is smaller than 6″, the smallest object which could be resolved with our instrument. At the estimated distance of the CrA dark cloud, the separation of the optical and infrared centers is approximately 10^{-2} pc. The observed magnitudes are summarized in table 1. *It seems quite clear that a very luminous infrared source is closely associated with the optical counterpart of a Herbig-Haro object*. This statement represents the hard observational result of this contribution.

III. INTERPRETATION

The infrared spectral energy distribution of the Herbig-Haro object is plotted in figure 3 along with the observed distributions for three emission-line variables of the Orion population located in the same region, R, S, and T CrA. With the exception of the 22-μ points which are taken from Knacke *et al.* (1973), all observations were obtained at the KPNO 50-inch telescope by the authors. The near-infrared ($\lambda \leq 10\ \mu$) spectra of the three stars seem best explained by free-free emission from a relatively cool ($T \sim 3000°$ K) circumstellar gas envelope. Low-temperature ($T \sim 100°$–$200°$ K) dust may begin to contribute to the infrared flux at 10 μ and actually dominate at 22 μ. The 5 to 12.6 μ spectrum of the Herbig-Haro object is quite similar to the spectra of R, S, and T CrA. However, the near-infrared portion of its spectrum is far too steep to be explained as free-free emission from a cool gas. This steep spectrum seems best explained by supposing that a T Tauri–like object is embedded deep within the dark cloud and is therefore heavily obscured and reddened. By assuming the reddened spectrum to be identical to that of R CrA, we derive a value of $A_v \sim 15$ mag; a larger value of A_v would be derived if the intrinsic spectrum of this object is more nearly similar to those of S CrA or T CrA.

By assuming that the infrared source is embedded within the dense concentration illustrated in figure 1, we can estimate a density for this region. At a distance of 150 pc (Gaposchkin and Greenstein 1936), the concentration has a linear diameter of 0.13 pc. Combining this size with our lower limit to the visual extinction yields a density estimate of at least 2×10^5 cm^{-3} under the assumption of a normal interstellar gas-to-dust ratio. This density for the dark material is ~ 100 times higher than that inferred from the spectrum of Herbig-Haro objects (Böhm, Perry, and Schwartz 1973). We note that this density is considerably higher than the values typically assumed to apply in dark clouds. In our opinion, however, there is no reason to suspect that values considerably higher than that quoted above may be found when detailed radio studies are carried out of the CrA and other dark cloud regions.

We would like to propose that the optical Herbig-Haro object is, in this case, a reflection nebula, illuminated by the infrared source; the infrared source we suppose to be a young star surrounded by a nebula with spectroscopic characteristics similar to the nebulosity surrounding T Tauri. We believe this hypothesis to have the following attractive features:

1) It avoids the serious energy problems one must face in ionizing gaseous material at densities as high as 2×10^5. The photoionizing flux required to produce the observed Hα strength in the Herbig-Haro object by a recombination process can be estimated from the product, ϕ, of the object radius times (density)$^{2/3}$. From the apparent optical extent of the CrA Herbig-Haro object, we derive $\phi \sim 60$ pc cm^{-2}. For the Herbig-Haro object in NGC 2068, the value of ϕ is ~ 100 pc cm^{-2}. An O5 or O6 star of luminosity $\sim 10^5\ L_\odot$ embedded within the dark cloud is required in order to supply the necessary ultraviolet flux for photoionization (Spitzer 1968). While the observed infrared brightness ($L_{IR} \geqslant 13\ L_\odot$) of the CrA Herbig-Haro object does not exclude this possibility, the strength of the [O I] features relative to the hydrogen lines and [O II] lines in other Herbig-Haro objects suggests that the large region responsible for producing the Herbig-Haro spectrum is only partially ionized throughout. This result probably renders an explanation based on radiative processes inoperative (Osterbrock 1958). Collisional ionization of the gas requires a minimum mass flux of $3 \times 10^{-2}\ M_\odot$ per year of particles ejected from the star at a velocity of 300 km s^{-1}; such demands would make the Herbig-Haro phenomenon extremely short-lived, and we reject this possibility as unlikely.

2) The light variations in H-H 2 (Herbig 1969) might be explained by changes in the brightness of a

single illuminating star and circumstellar envelope complex. If there are multiple scatterings before the light from the embedded object reaches the individual knots in H-H 2, phase shifts in brightness and spectral variations of several months might result.

3) The specific intensity of the emission lines has been reduced in transit through the dark cloud, thus avoiding the discrepancy between the surface brightness predicted by Böhm (1956) from the forbidden line ratios observed in H-H 1 and the observed surface brightness in the Balmer lines, which is a factor of 25 lower. The problems for Herbig-Haro objects of larger angular size, such as the object in NGC 2068, must grow even more severe.

4) Our hypothesis produces a natural explanation for the underlying continuum, which is not understood on any of the other schemes.

We are forced to postulate the existence of a circumstellar nebula surrounding the T Tauri–like object similar to, but much larger or more luminous than, the nebulae surrounding T Tau and HL Tau (in order that the unusual emission-line spectrum dominate the more normal T Tauri spectrum). It is not unreasonable to assume that nebulae with higher emission measures surround stars in very early phases of their evolution. We note in this regard the arguments of Knacke *et al.* (1973) which offer some evidence that the CrA T association might be among the youngest of such groups. It is perhaps not too far-fetched to speculate that Herbig-Haro objects manifest themselves only within a dark cloud in which star formation has taken place very recently and where there remain "clumpy" regions of high density indicative of recent fragmentation.

Objections to our picture are raised by the observations of Böhm *et al.* (1973). They report velocity variations of 15 km s^{-1} across Herbig-Haro object 1 from observations of the Balmer lines. They also report a systematic variation of the [O II] doublet ratio across the object. It is quite possible that their spectra of H-H 1 are contaminated by the spectrum of the bright reflection nebula which surrounds the complex emission-line object V380 Ori and extends into the vicinity of H-H 1. However, if their results are confirmed, they would cast significant doubt on our interpretation and favor models casting H-H objects as unusual prestellar entities.

IV. SUMMARY

We have detected a strong infrared source which lies within several hundredths of a parsec of an optically observed Herbig-Haro object. We suggest that the optical object may represent the scattered spectrum of a very young T Tauri star plus nebula complex embedded within the dense parts of the Corona Austrina dark cloud. This explanation makes no statement regarding the exact physical mechanism responsible for the excitation of the unusual line spectrum which characterizes both the Herbig-Haro objects and the T Tauri nebulae. However, if our picture is valid, the Herbig-Haro phenomenon is removed from the realm of an undefined, somewhat mysterious prestellar stage of evolution to that of a well known, if not yet well understood, pre–main-sequence phase.

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1974ApJ...187...83S

PLATE 1

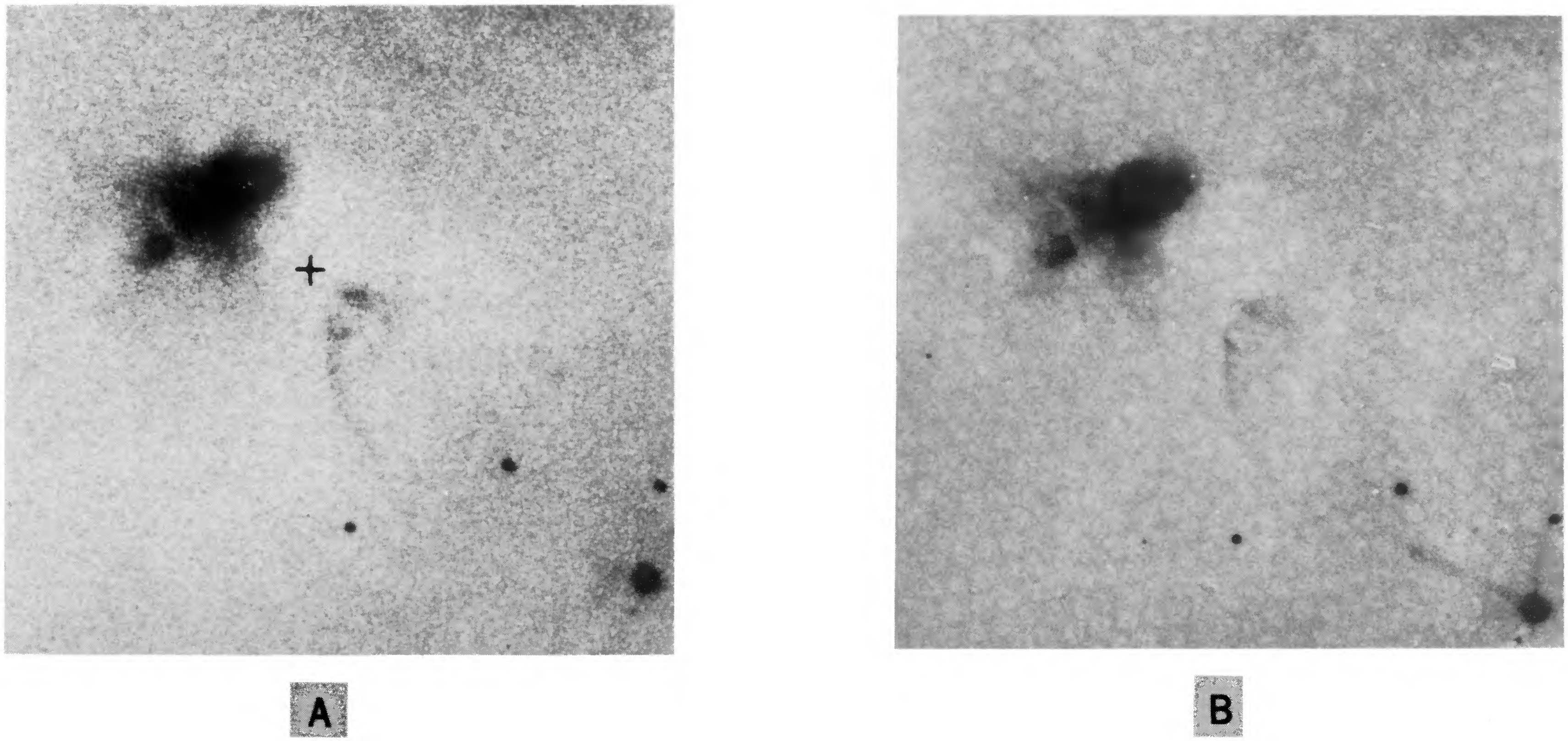

FIG. 1*a*.—The region surrounding the Herbig-Haro object in Corona Austrina. This photograph was obtained with the Michigan Schmidt telescope at Cerro Tololo Inter-American Observatory; a water-hyped 098-02 emulsion along with an RG-8 filter was used. Note particularly the white, roughly spherical condensation in which the H-H object appears. We interpret this condensation as a very dense region within the CrA dark cloud complex. The infrared source location is indicated by a +.

FIG. 1*b*.—A photograph taken with an ITT S-20 image tube filtered to include the wavelength range 7000–8200 Å. There is no evidence for a stellar object associated with the dark concentration or the Herbig-Haro object. In both photographs, north is at the top and east to the left. The scale is approximately 3.7″ mm^{-1}.

STROM *et al.* (*see* page 84)

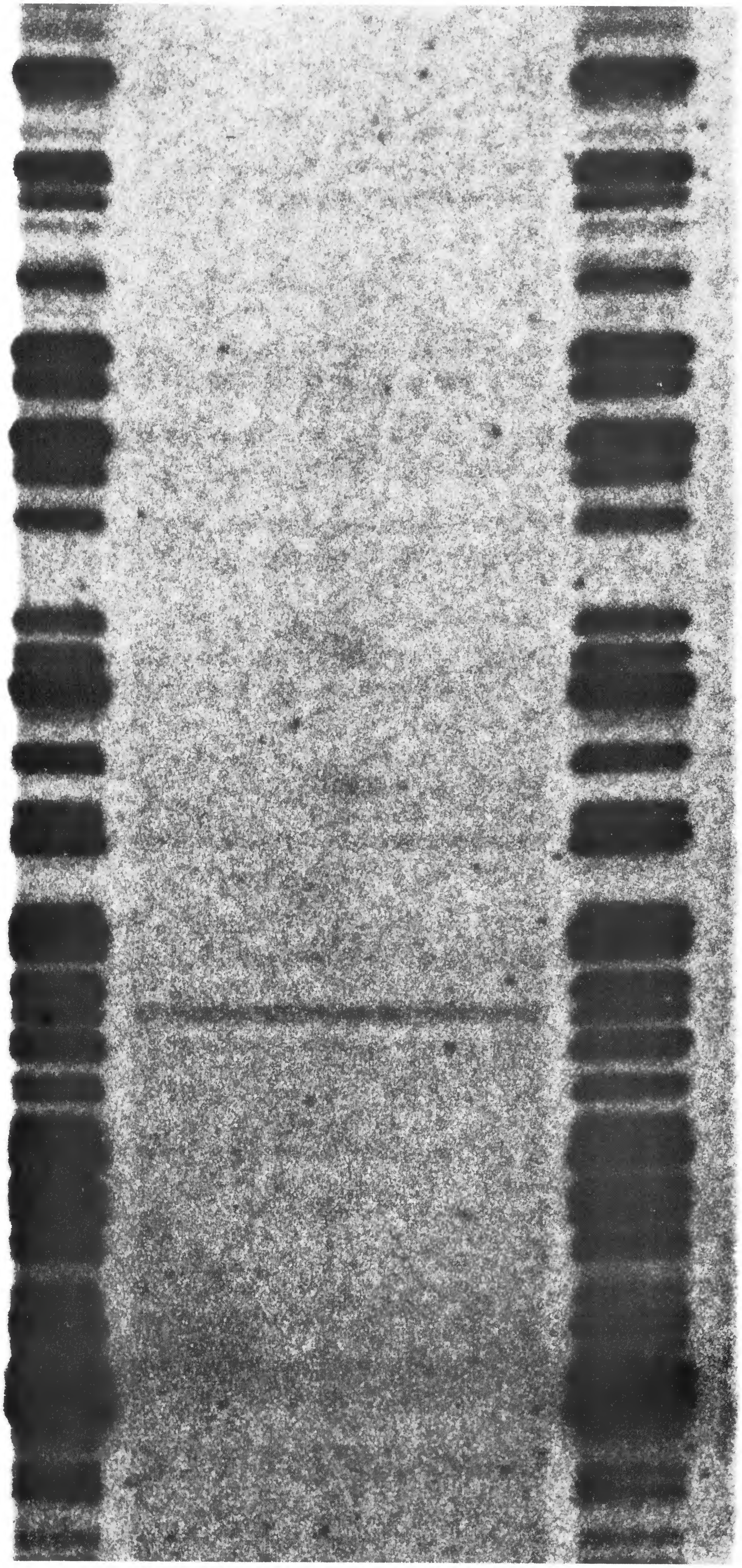

FIG. 2.—An image-tube spectrogram at a dispersion of 240 Å mm^{-1} of the Herbig-Haro object taken with the Lynds image-tube spectrograph on the KPNO 2.1-m telescope. The features extending the full length between the comparison spectra are atmospheric, the strongest being the [O I] line at 6300 Å. The narrow continuous spectrum and the emission lines Hα and [S II] at 6717 and 6731 Å arise in the H-H object.

STROM *et al.* (*see* page 85)