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Near infrared spectroscopy of protostars

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Observational study of protostars and their immediate environs has recently become possible as a result of advances in infrared spectroscopy, especially in the near infrared (λ = 2–5 μm). Although such stars are totally obscured at optical wavelengths by the enshrouding dust and gas from which they formed, the near infrared spectroscopy has yielded detection of emission lines from both ionized gas and high excitation molecular gas ($T \gtrsim 2000$ K) probably within a few astronomical units of several such sources (e.g. the BN object in the Orion nebula). The former lines provide the first constraints on the spectral type and temperature of the protostar; the latter reveal the physical conditions (density and temperature) and gas dynamics in the immediate protostellar nebula.

Data on the BN object covering the CO, ^{13}CO, and H_2 vibrational bands and the H II lines are presented as an illustration of these techniques.

1. Introduction

At present the phase of stellar evolution most unknown and mysterious to us is the brief period of conception, birth and adolescence during which the nascent star is enshrouded within its marsupial cloud. Within the giant molecular clouds, millimetre line maps show many inhomogeneities with density contrast a factor of 10^2–10^3 above the average; unfortunately in no instance is there clearcut evidence of *incipient* star formation. With respect to the latter phases, birth and adolescence, near infrared photometry has revealed many examples of compact energy sources within the cloud cores; yet it is never clear from the continuum data which of the two phases the star is in. Perhaps the only resolution to this quandary lies in infrared spectroscopy: the capability of measuring gas kinematics adjacent to the star can discriminate infall, outflow or orbital motions (Hall *et al.* 1978); the possibility of determining the u.v. emission rate from recombination lines and comparison with the i.r. luminosity can discriminate between main sequence and pre-main sequence stars (see, for example, Simon *et al.* 1979; Thompson 1981).

Spectroscopy in the near and mid-infrared is also revealing for the first time the extraordinary rich environment within the cloud cores. Molecular hydrogen emission at 2 μm has now been detected in a dozen such regions; this emission probably arises from gas at $T_k \approx 2000$ K heated in high-velocity shock fronts (Gautier *et al.* 1976; Beckwith *et al.* 1978, 1979; Nadeau & Geballe 1979; Scoville *et al.* 1981). (Often the presence of H_2 emission is correlated with high-velocity emission in the millimetre wavelength lines (e.g. CO $J = 1 \rightarrow 0$).) Unexpected gas kinematics and extreme excitation conditions also show up in the infrared observations of CO vibrational and pure rotational transitions (Hall *et al.* 1978; Watson *et al.* 1980; see also below). Since the observed dynamic motions are probably disruptive of star formation in the cloud core, and constitute a significant energy input to the interstellar clouds, it is extremely important to understand the relation of this activity to the coincident star formation.

A representative sample of infrared sources observed in dense molecular clouds is given in table 1 with estimates of their luminosity (infrared + visual) and indications of whether they have associated ionized gas, H_2 emission, or high-velocity millimetre CO line emission ($\Delta V \gtrsim 20\ \mathrm{km\ s^{-1}}$). The sources listed here range from LkHα 101, which is relatively unextincted, to W3 IRS5 and IRc-4 in Orion, which despite their high luminosities are hardly detectable at 2 μm owing to extremely large amounts of circumstellar and foreground dust.

Table 1. Sample of young stars and protostars

object	$L_{\mathrm{i.r.}}/L_{\odot}$	H II *f–f* or Br lines	H_2† emission	CO† high-velocity
BN	$> 2 \times 10^3$	yes[1,2,3]	yes[4,5]	yes[6]
OMC-1 IRc-4	10^4–10^5	—	yes[4,7]	yes[6]
Lk Hα101	2×10^4	yes[8,9,10]	no[10]	no[11]
S140 IRS-1	10^4	yes[10]	yes[4,10]	yes[11]
L1551 IRS-5	25	yes[13]	—	yes[12]
W3(OH)	*ca.* 10^5	yes	yes[4]	yes[11]
W3 IRS-5	*ca.* 10^5	—	—	yes[11]

References: 1, Grasdalen (1976); 2, Joyce *et al.* (1978); 3, Hall *et al.* (1978); 4, Gautier *et al.* (1976); 5, Scoville *et al.* (1976); 6, Kwan & Scoville (1976); 7, Beckwith *et al.* (1978); 8, Simon *et al.* (1979); 9, Thompson *et al.* (1977); 10, Kleinmann *et al.* (1981); 11, Bally & Lada (1981); 12, Snell *et al.* (1980); 13, Beiging *et al.* (1981).

† The H_2 emission at 2 μm and the CO $J = 1 \rightarrow 0$ high-velocity emission ($\Delta v > 20\ \mathrm{km\ s^{-1}}$) when noted with a 'yes' are seen within *ca.* 1′ of the star. It is possible and in some cases likely that they are related to another object in the region.

The former is surely a star that has already reached the main sequence; the latter two are probably the best candidates for stars that are still forming. The luminosities range from only *ca.* 25 $L_{\odot}$ for IRS5 in L1551 up to a very uncertain $10^5\ L_{\odot}$ for W3(OH) and W3 IRS5. Usually there are highly supersonic gas disturbances in the *vicinity* as indicated by either the H_2 emission or the high velocity millimetre lines. The best case for causal connection between the energy source and this dynamic activity is probably L1551, where there is apparently only one source present and optical emission lines and proper motions in two nearby H–H objects suggest a high-velocity wind from the star (see Snell *et al.* 1981). In the other regions, the disturbance could be related to a source other than the one listed in table 1.

The most thoroughly studied object in table 1 is the Becklin–Neugebauer source in Orion. Its relatively strong continuum at $\lambda = 2$–5 μm makes it feasible not only to detect emission lines but also to measure at high frequency resolution the absorption in front of the source. Although it is likely that this star has already reached the main sequence, the variety of phenomena seen here suggest that it is still surrounded by a pre-solar nebula and is currently dispersing this gas. The near infrared spectroscopy reveals both an extremely compact H II region (detected by means of the Br α line by Grasdalen 1976) and ultra-high excitation molecular gas (detected by means of CO emission at 2.3 μm by Scoville *et al.* (1979)). Both regions are probably within a few astronomical units of the central star.

In the review below, I concentrate on the near infrared spectroscopy of BN in the hope not only of illuminating this particularly intriguing source but also of illustrating the potential of

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such spectroscopy done at a resolution sufficient to measure the molecular bands. Many of the observational phenomena detected in BN will undoubtedly be seen in future observations of the younger sources (e.g. IRc-4).

The data on BN presented in the next section were obtained with the aid of the Fourier Transform spectrometer at the KPNO 4 m telescope and analysed in collaboration with D. N. B. Hall, S. G. Kleinmann and S. T. Ridgway (Scoville *et al.* 1981). The spectra involved integrations of several hours duration with apertures of 2″ for $\lambda \gtrsim 3.8$ μm and 3.75″ for $\lambda = 2.0$–2.4 μm. The spectral resolution ($\Delta\sigma = 0.07$–$0.3\ \mathrm{cm^{-1}}$) corresponds to $\Delta V = 7$–$20\ \mathrm{km\,s^{-1}}$.

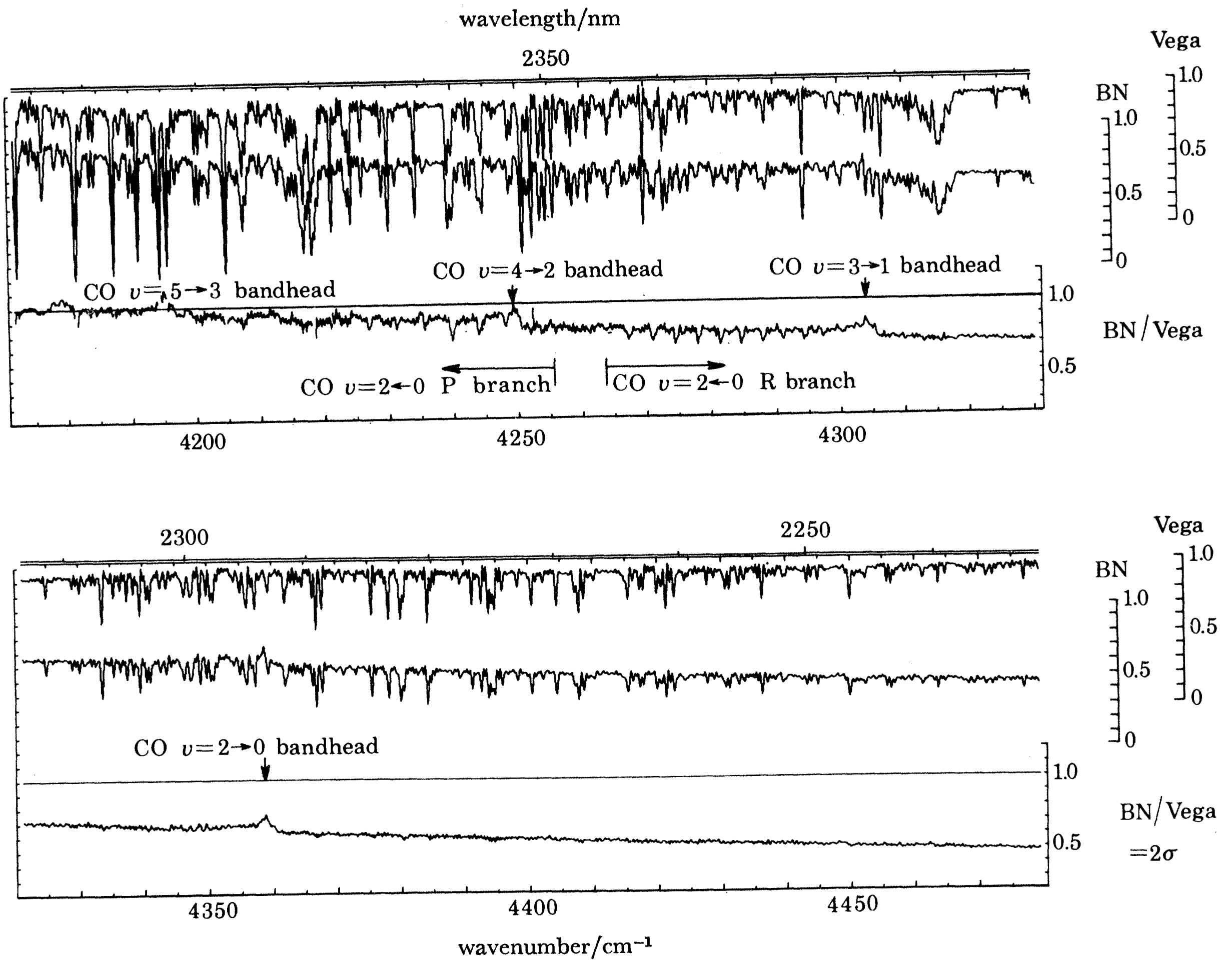

FIGURE 1. Spectra of BN and the comparison star (Vega) are shown in the vicinity of the $\lambda = 2.3$ μm CO overtone bands. Absorption in the Earth's atmosphere is removed by plotting the ratio of BN to Vega. The ratio spectrum (bottom trace in each panel) shows CO absorption at low J in the $v = 2 \leftarrow 0$ band and emission features at the bandheads of $v = 2 \rightarrow 0$, $3 \rightarrow 1$ and $4 \rightarrow 2$. Frequency resolution is 0.3 cm^{-1}, equivalent to 20 km s^{-1}.

2. Spectroscopy of BN

Table 2 lists the lines identified in the $\lambda = 2$–5 μm spectra of BN. The lines believed to be closely associated with BN include those of H I, Na I, and the CO *emission* features at $\lambda = 2.3$ and 4.6 μm. The CO absorption and H_2 emission probably arise in gas further out along the line of sight to BN.

(*a*) CO

The portion of the K-band spectrum covering the CO ($\Delta v = 2$) overtone bands is shown in figure 1. At low J in the $v = 2 \leftarrow 0$ band a series of well resolved absorption lines are seen; at high J on the R-branch of each of the first three bands ($v = 2 \rightarrow 0$, $3 \rightarrow 1$ and $4 \rightarrow 2$) broad emission features are seen at the bandheads. In the fundamental band ($v = 1 \leftarrow 0$) the same absorbing gas is seen but owing to the factor of 135 increase in the absorption coefficients the

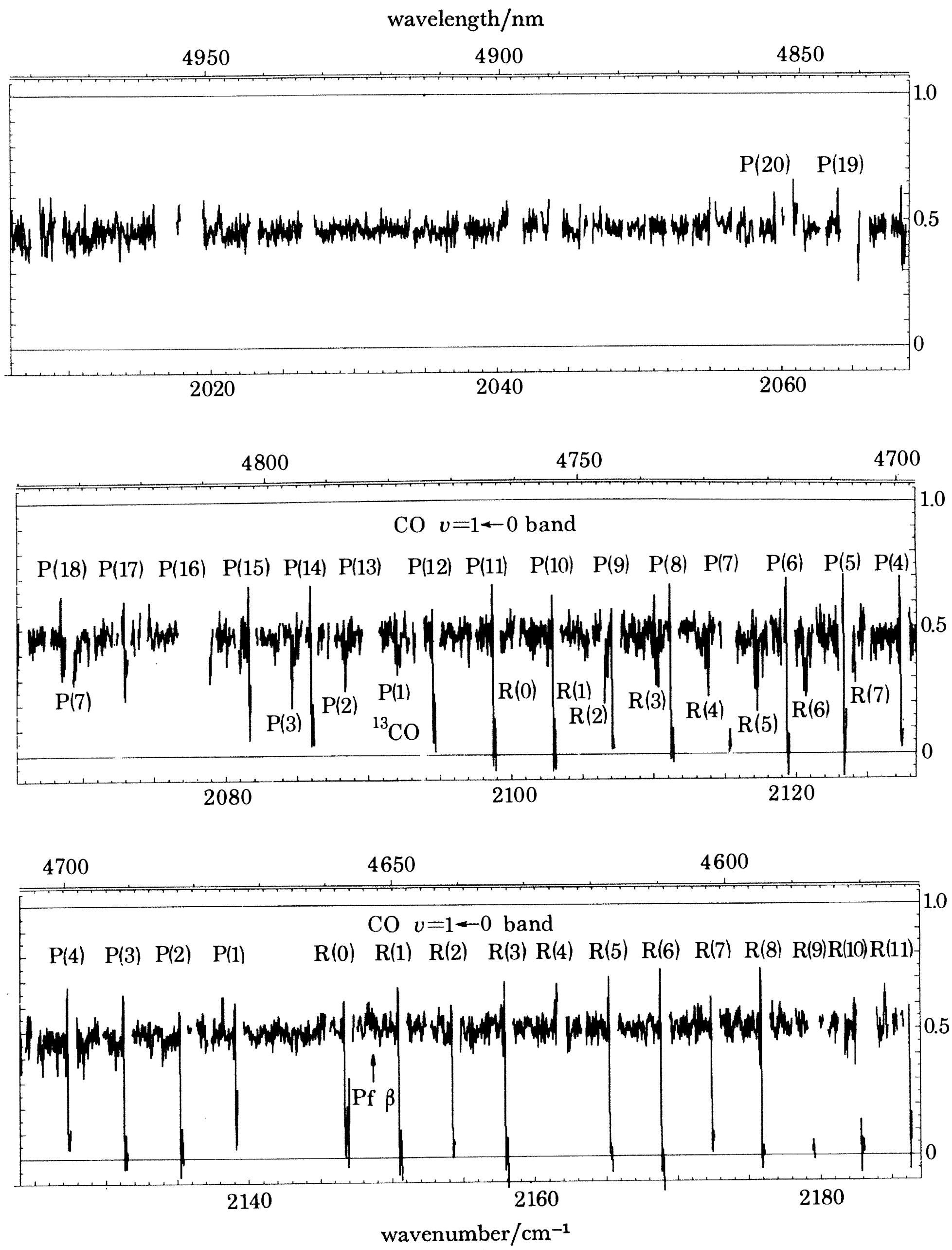

FIGURE 2. Ratio spectrum of BN at $\lambda = 4.5$–5.0 μm covering the CO and ^{13}CO fundamental bands and the Pf β recombination line. (Gaps in the ratio spectrum correspond to telluric absorption greater than 55 %.) Resolution is 0.07 cm^{-1}, corresponding to 7 km s^{-1}.

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^{12}CO lines are very heavily saturated except at $J > 15$ (see figure 2). On the other hand, at 4.6 μm the entire ^{13}CO band is still unsaturated and can be measured with high precision since there is no significant telluric ^{13}CO absorption.

(i) *Absorption at* 8.6 *and* −17.5 km s^{-1}

Figure 3 shows the kinematic profiles of the CO obtained by averaging all the detectable rotation–vibration lines in the CO $v = 1 \leftarrow 0$, $v = 2 \leftarrow 0$ bands and the ^{13}CO $v = 1 \leftarrow 0$

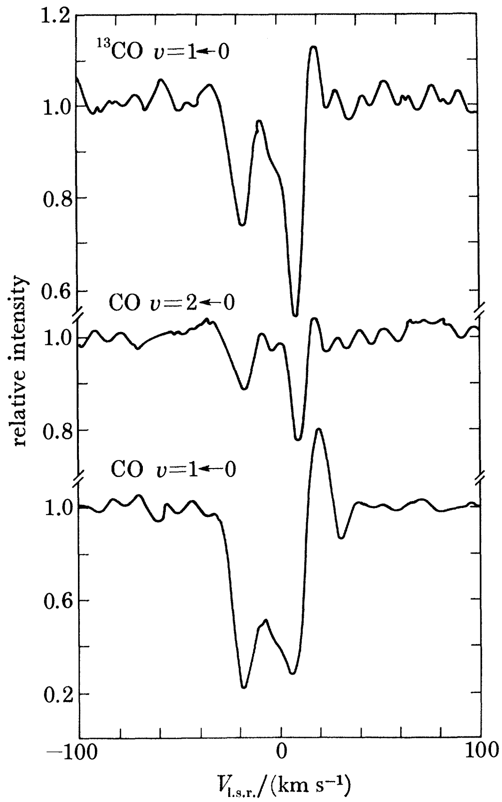

FIGURE 3. Kinematic profiles for the $v = 1 \leftarrow 0$ CO and ^{13}CO bands and the $v = 2 \leftarrow 0$ CO band obtained by averaging all lines detected in each band. Velocity resolution is 7 km s^{-1}. The fundamental bands of CO and ^{13}CO show two absorption velocities corresponding to OMC-1 (+9 km s^{-1}) and the 'expanding shell' (−17 km s^{-1}), plus an emission line at 20 km s^{-1} produced close to BN.

TABLE 2. SPECTRAL FEATURES IN BN

		transitions		λ/μm
atomic	H I	Brα $n = 5 \rightarrow 4$		4.05
		Brγ $n = 7 \rightarrow 4$		2.16
		Pfβ $n = 7 \rightarrow 5$		4.66
		Pfγ $n = 8 \rightarrow 5$		3.74
	Na I	$^2S - ^2P^0$		2.21
molecular	H_2	$v = 1 \rightarrow 0$	S(2)—Q(3)	2.2–2.4
		$v = 2 \rightarrow 1$	S(1)	2.25
	CO	$v = 1 \leftrightarrow 0$	R(12)—P(20)	4.6–4.9
		$v = 2 \leftarrow 0$	P(12)—R(11)	2.33
		$v = 4 \rightarrow 2$,	$3 \rightarrow 1$, $2 \rightarrow 0$ bandheads	2.33
	^{13}CO	$v = 1 \leftrightarrow 0$	R(7)—P(7)	4.7–4.8

band. At the high resolution of these data (ΔV = 7 km s^{-1}), the absorbing gas is seen to consist of two discrete velocities, $V_{l.s.r.} = +8.6$ and -17.5 km s^{-1}, first measured by Hall *et al.* (1978). The former is at the same velocity as OMC-1 as determined from millimetre line data; this absorption thus samples the foreground column in the quiescent cloud. Hall *et al.* (1978) surmised that the blue component is formed in an expanding shell situated in front of BN but still within the cloud core – perhaps related to the high-velocity 'plateau' source seen in the millimetre CO line.

Owing to the saturation of the CO fundamental band, the molecular column density and rotational temperature are best determined from the overtone lines. For the OMC-1 feature we find $T_r = 150 \pm 15$ K and a total CO column density $N_{CO} = (7.5 \pm 1.5) \times 10^{18}$ cm^{-2}. The blue absorption feature shows a similar rotational distribution but has a 30% lower column density. The low rotational temperature of both absorption systems strongly suggests that neither is formed within the circumstellar envelope of BN at R $\lesssim$ 30 AU. The CO/^{13}CO isotope ratio obtained from comparison of the CO $v = 2 \leftarrow 0$ and ^{13}CO $v = 1 \leftarrow 0$ absorption is 96 ± 5, in good agreement with the solar system [C/^{13}C] ratio of 89. Since both bands are probably optically thin (though not by a large margin) and arise from the same lower state rotational levels, this estimate does not entail large corrections for line saturation or any assumptions concerning the rotational excitation of the separate isotopes.

(ii) *Emission at* 4.6 μm

The third Doppler component seen in figures 2 and 3, the emission feature at $V_{l.s.r.} = 20$ km s^{-1}, is probably more closely associated with BN. Both the distribution of line intensities as a function of J and the possible detection of ^{13}CO emission (see figure 3) suggest that the ^{12}CO emission is optically thick. The rate at which the emission falls off with increasing J (between P17 and P20 in figure 2), suggests a rotational temperature of *ca.* 600 K for this gas. The fact that this temperature is much greater than that of the absorption lines implies that the emission should not be linked to either absorption system in the fashion of a P Cygni profile from an expanding envelope.

At the densities expected in the envelope around BN, we expect that the gas and dust will be in close thermal equilibrium ($T_k \approx T_{dust}$). It is then natural to place the CO emission region just outside the dust 'photosphere' since the colour temperature of the observed near infrared continuum is $T_c \approx$ 500–600 K (Becklin *et al.* 1973). Assuming that the continuum is not simply that of a highly reddened star, the radius of this 'photosphere' must be greater than 25 AU, corresponding to the radius of a black body with the observed temperature and luminosity. Recent speckle interferometry at 3.5 and 4.8 μm indicates that the actual size is within a factor of two of this lower limit (Foy *et al.* 1979).

(iii) *Bandhead emission at* 2.3 μm

The last CO feature, perhaps the most unusual, is the bandhead emission seen at $\lambda = 2.3$ μm. Rotational temperatures greater than 2000 K are required to populate $J = 50$ significantly and give the observed shapes of the bands; the gas producing this emission is therefore quite distinct from that producing the narrow 4.6 μm emission lines. If the bandheads are optically thin, then the relative intensities of the separate bands imply a vibrational temperature of 3500 ± 500 K. Since the radiative decay rate out of the highest observed level ($v = 4$, $J = 50$) at $E/k \approx 19000$ K is 100 s^{-1}, the density required to excite these levels is $n_{H+H_2} \gtrsim 10^{10}$–$10^{11}$ cm^{-3}.

Based upon our upper limits to the fundamental band emission from the same rotationally hot CO (see figure 2), we set a lower limit to the optical depth such that the radius of the emission region must be less than 1.5 AU (Scoville *et al.* 1979). Theoretical analysis of the possible collisional and i.r. pumping mechanisms for CO also imply a size $R \lesssim 5$ AU (Scoville *et al.* 1980). The width of the individual lines within the bandheads are in the range 50–100 km s^{-1}; the mean velocity is estimated as $V_{\text{l.s.r.}} = +20 \pm 10$ km s^{-1}.

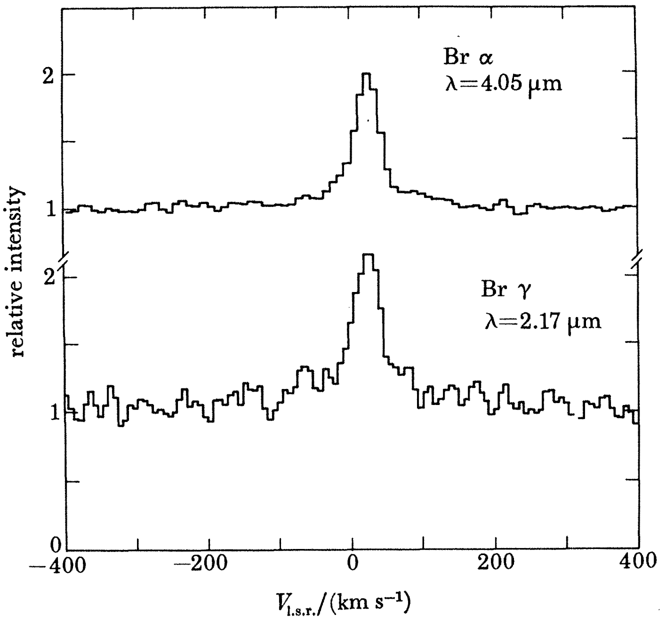

FIGURE 4. Profiles of the hydrogen Br α (λ = 4.05 μm) and Br γ (λ = 2.17 μm) lines in BN. Velocity resolution is 20 km s^{-1}.

(*b*) *Ionized gas*

Figure 4 shows the profiles of the Br α and Br γ lines at λ = 4.05 and 2.16 μm. Each line exhibits two components: a narrow core at $V_{\text{l.s.r.}} = +21$ km s^{-1} with $\Delta V_{\text{f.w.h.m.}} = 38$ km s^{-1} and broad wings detectable over a full extent of *ca.* 350 km s^{-1}. Both components should be identified with BN since the observed Br α flux in the 2″ aperture is too high by a factor of 30 to be from M42 and their centre velocity is red-shifted 24 km s^{-1} relative to M42 (Hall *et al.* 1978).

Comparing the observed Br γ/Br α flux ratio of 0.096 with the ratio of 0.42 expected for recombination in a dense plasma, we deduce a reddening of E(2.16–4.05 μm) = 1.6 magnitudes implying an extinction at Br α of $A_{4.05\,\mu\text{m}} = 0.7$ magnitudes for the standard van de Hulst no. 15 dust extinction law. The photoionization of this H II region requires a source of Lyman continuum photons equivalent to a main sequence B0–B0.5 star.† The total luminosity of such a star is 1–2 × $10^4\,L_\odot$ (Panagia 1973). This luminosity is an order of magnitude greater than that obtained by directly integrating the infrared photometry at $\lambda \lesssim 20$ μm for BN

† The Na I doublet observed at λ = 2.21 μm furnishes an additional constraint on the u.v. flux of the BN star. The transition is probably excited into fluorescence after absorption from the ground state of u.v. at 330 nm. The observed flux in the i.r. doublet can be accounted for with pumping by about 10% the u.v. flux expected from a B0 main sequence star. The emission lines are broad and centred at $V_{\text{l.s.r.}} \approx 24$ km s^{-1}.

(Becklin *et al.* 1973), and about three times greater than the observed luminosity corrected for extinction as inferred from the 10 μm silicate absorption (Downes *et al.* 1981).

The size of the H II region in BN is limited to $R \lesssim 15$ AU based upon the absence of detectable free–free radio continuum (Righini-Cohen *et al.* 1981). For R = 1–15 AU the emission measure deduced from the Br α line implies an electron density $n_e = 3 \times 10^9$ to 6×10^7 cm^{-3} and mass $M_{\mathrm{H\,II}} = 4 \times 10^{-8}$ to $2 \times 10^{-6}\, M_{\odot}$. If the high-velocity wings originate in a wind with outflow velocity of 100 km s^{-1}, then the annual mass loss rate is $M \approx 10^{-6}\, M_{\odot}$.

(*c*) *The nature of* BN

Based on the foregoing spectroscopic data, there is no evidence that the central star in BN is still accreting matter. On the contrary, all the data are consistent with the central star's being on the main sequence with spectral class B0–B0.5 ($T_{\mathrm{eff}} \approx 28$ kK, $L \approx 1$–$2 \times 10^4\, L_{\odot}$).

Most fascinating is the immediate circumstellar nebula. We find compelling evidence of both an ultra-compact H II region and high-density molecular gas within a few astronomical units of the star. A natural situation in which both may arise would be a dense, neutral disc, presumably a pre-solar nebula with the young star located at the centre. The H II region could be expected at the centre of the disc where u.v. from the star would ionize and ablate gas from the disc. If the dust around BN is primarily confined to a disc, one may also understand the fact that the luminosity derived from near infrared photometry is one-third to one-tenth of that expected for the star required to ionize the H II region. The similarity of the density estimates required for the CO bandhead emission and the emission measure of the H II region (if it is only *ca.* 1 AU in size) is consistent with the notion that the H II interfaces with the CO emission region. The neutral gas associated with BN probably extends out to at least 25 AU since the 4.6 μm CO emission is best modelled as arising just outside the dust 'photosphere'.

In so far as no significant difference is measured in the Br γ/Br α ratio for the high and low velocity H II, both components must lie behind similar columns of dust, and it is likely they are physically associated. It is possible that the low-velocity H II is gas ionized and ablated off the neutral disc by the u.v. from the star; the high-velocity H II is more likely to be a wind directly from the star. The wind interpretation is suggested by the observation that the rate of momentum transport in the high-velocity H II is nearly equal to the radiation pressure limit (L_{BN}/c); this is a general characteristic of the winds observed in early-type stars (see Abbott *et al.* 1980). The momentum flux of the high-velocity H II is insufficient by a factor of *ca.* 500 to account for the high-velocity flows seen at $R \approx 10^{17}$ cm in the Orion cloud core.

The velocities of four spectroscopic tracers (H II, Na I and two CO emission features) were all found to be $V_{\mathrm{l.s.r.}} \approx 21$ km s^{-1}. Since they are thought to be closely associated with BN but arise in very different environments (both neutral and ionized) at radii between *ca.* 1 AU and 30 AU, we infer that 21 km s^{-1} is in fact the systemic velocity of BN and its surrounding nebula. This surprising result implies a motion of BN into OMC-1 at +12 km s^{-1} along the line-of-sight. If BN is not in a binary system, it will leave the cloud core ($R \lesssim 10^{17}$ cm) on a timescale of only a few thousand years!

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3. Spectroscopy of other young stars

Our discussion above concentrated on BN to illustrate the tremendous potential of moderately 'complete' near i.r. spectroscopy at a resolution sufficient to resolve kinematic features. In general, the kinematic information is absolutely necessary to define the evolutionary state (accretion or dispersion) of the protostellar nebula. Although high resolution is imperative for the molecular absorption line observations, lower resolution data obtained with grating spectrometers and FTS have been used for extensive work on the H II emission lines, primarily Br γ (see Thompson 1981) and Br α (Simon *et al.* 1980).

If *both* Br α and Br γ are observed, or the radio flux has been measured, these data yield estimates of the foreground extinction and the u.v. emission rate of the star. In general, these studies find the required u.v. luminosities to correlate with the photometric luminosity, but not with the functional dependence expected for main sequence stars. In particular, Thompson (1981) notes that the stars with intermediate luminosity often have a tenfold higher implied u.v. production rate than a main sequence star with the measured photometric luminosity. Two prime examples are GL490 (Thompson & Tokunaga 1979) and BN. Although it has been argued that the additional u.v. could arise from accretion in a viscous disc (Thompson 1981), the kinematic data presented in the previous section for BN showed no evidence of infall in the H II gas. For BN, it appears more likely that the measured photometric luminosity is an underestimate of the actual stellar output. If the dust surrounding BN is in a disc, or at least not spherically symmetrical about the star, a large fraction of the short wavelength photons may escape to a distance where they become confused with those of the other nearby sources. In cases where the surrounding dust is not symmetrical about the star or where there is source confusion, the recombination lines will yield a much more reliable estimate of the luminosity, provided the star is on the main sequence.

The high-resolution spectroscopy of BN described here was done in collaboration with Don Hall, Susan Kleinmann, and Steve Ridgeway and will be published in *Astrophysical Journal*. This research, contribution no. 483 of the Five College Astronomy Department, was partly supported by N.S.F. grant AST 80-26702 to the Five College Radio Astronomy Observatory and by the Institute for Astronomy, University of Hawaii.

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