Spectroscopic constraints on outflows from BN-type objects

Janet E. Drew
Department of Physics,
Nuclear Physics Laboratory,
Keble Road,
Oxford,
OX1 3RH.

Abstract.
New high-quality high spectral resolution observations of the HI line emission from massive young stellar objects are described and discussed. It is proposed that two distinct physical components contribute to the observed emission. One of these is an optically-thick high-velocity stellar wind, the other a more slowly moving optically-thin volume of gas that may, in the case of S106IR at least, be caused by mass loading of the stellar wind. This decomposition is shown to resolve a long-standing problem regarding the relative widths of high and low opacity lines.

Key words: Infrared: stars – stars: early-type, formation – ISM: jets and outflows

1 Introduction

Infrared spectroscopy is now coming of age. The first spectrometers able to operate on astronomical telescopes at wavelengths between 1μ and 5μm were commissioned in a few years around 1980. Their design had to work around the limitation that the area detectors available to optical astronomers had yet to be developed for infrared use – hence the appearance of scanning Fabry-Perot and Fourier Transform spectrometers, alongside grating spectrometers such as UKIRT's CGS2 built around a 7-element detector. This has changed in that many telescopes now have 58×62 IR arrays and are upgrading to 256×256 devices. The possibility of optical-style spectroscopy has brought with it the opportunity for enormous improvements in data quality. High precision at high spectral resolution is now achievable. The subject of this paper, the outflows from deeply embedded massive YSOs, is a research topic that stands to gain much from this advance. The observations made of these objects with the first-generation spectrometers during the first half of the 1980s defined the problem – data from the second generation may go along way toward solving them. In this paper, some of the new observations of BN-type objects obtained with Cooled Grating Spectrograph No. 4 (CGS4) on UKIRT are presented and used to motivate a modified and, it is to be hoped, more fruitful interpretation.

The prototype of the massive YSOs is the Becklin-Neugebauer Object in OMC-1, hence the term 'BN-type object'. These are extremely luminous (L $\gtrsim 10^4 L_\odot$) heavily-obscured (A_V upward of $\sim$15) sources found in regions of massive star formation. So far, none of them has been spatially-resolved at infrared wavelengths. They are just becoming resolvable in the radio domain (e.g. by the recently enhanced *MERLIN* network). An early review of their properties was written by

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Wynn-Williams (1982).

Their most intriguing characteristic is the evidence of outflow at rates over an order of magnitude higher than those sustained by late-O, early-B main sequence stars of comparable luminosity. That this is surprising has much to do with the supposition massive YSOs evolve so rapidly on to the main sequence that it is unlikely any known examples are still approaching it. Compared with normal OB stars, BN-type objects are strong radio sources for their bolometric luminosities but, like normal OB stars, their radio spectral indices fall in the range that is consistent with thermal emission from the $\sim 1/r^2$ density distribution associated with the far reaches of a stellar wind (i.e. $F_\nu \propto \nu^\alpha$ where $\alpha \gtrsim 0.6$). These measurements fix $\dot{M}/v_\infty$, while observed spectral line widths at IR wavelengths set lower limits on v_∞. Mass loss rates derived in this way are of the order of 10^{-6}–10^{-7} $M_\odot\,yr^{-1}$ (Simon *et al.* 1983).

The spectrum of a BN-type object in the infrared is typically made up of a strong highly-reddened continuum and velocity-broadened HI recombination line emission. The contrast of the line emission against the continuum varies greatly from object to object: in some (e.g. GL 2591) the line emission is very difficult to detect while in others (most notably S106IR) the strongest lines have peak fluxes several times that in the adjacent continuum. Another source of diversity within the class is to be found in the estimates of line flux ratios: there are cases where the conclusion that the HI lines are optically-thick is inescapable and examples where Recombination Case B ratios are approached. Chemical species other than hydrogen have been detected in one or two objects at more modest levels of emission (see Scoville *et al.* 1983 and Simon & Cassar 1984). The observed line-widths range from $\sim$100 km s^{-1} (FWHM) up to $\sim$300 km s^{-1}. If these velocities are representative of the terminal velocities attained, then we have another problem: main sequence OB stars of the same luminosity achieve much higher terminal velocities in the region of 1000 km s^{-1} or more.

The 'surprisingly high' mass loss rates and 'surprisingly low' outflow velocities have provoked two distinct interpretations. On the one hand, line profile synthesis models have been explored that treat the outflows as simple stellar winds from what are, in effect, bloated low-gravity stars (e.g. Felli *et al.* 1984). On the other, remnant protostellar disks have been blamed for the phenomena and analogies have been drawn with the barely less mysterious classical Be stars (e.g. Persson, McGregor & Campbell 1988). In the presence of what can now be seen as primitive data, neither interpretation could move to the point of decisive testing.

A further obscurity of this subject is the relation between BN-type objects ('outflow sources') and ultra-compact HII regions. The latter should distinguish themselves from the former by (i) exhibiting much narrower, optically-thin IR line emission (velocity widths $\lesssim$ 30 km s^{-1}), (ii) yielding radio spectral indices characteristic of HII region emission ($F_\nu \propto \nu^\alpha$ where $\alpha \sim 0$ in the optically-thin limit, or $\alpha \sim 2$ for optically-thick emission). This distinction is not always a clean one. For example, the source LkHα 101 (for which A_V happens to be low enough to allow the object to sneak into the Herbig Ae/Be star category) has an IR spectrum compatible with an HII region classification but a radio spectrum that fits well to the outflow model. Is this an outflow source or is it not? Even without this kind of confusion there remains the larger question regarding the evolutionary connection within and between the two groups, if any. Evolution or environment? Nature or nurture?

2 The line width problem

Early in the 1980s, Simon and collaborators set the basis for the interpretation of the IR HI line profiles and flux ratios (Simon *et al.* 1981 and 1983 being the key publications). Some obvious, but important, points were recognised. In particular, it was noted that optically-thicker emission lines must be as broad or broader than less opaque lines if both are produced within an outwardly accelerating radial outflow. For example, Brα should be at least as broad as either Brγ or Pfγ. The IR spectra themselves turned out to be rather uncooperative in this regard. A striking illustration of this is to be found in the observational study of Persson *et al.* (1984, see their Figure 4): they provided examples of comparisons between Brα and Brγ line profiles in the spectra of a number of objects that both conformed with and reversed the expected pattern.

A related problem emerged in attempting to fit observations of the Brα and Pfγ line profiles in the spectrum of S106IR (Bunn & Drew 1992; the observations being due to Garden & Geballe 1986). It was found that the ratio between the line fluxes was very hard to reconcile with the constraint on the mass loss rate provided by radio flux measurements (Felli *et al.* 1984). The observed ratio was suspiciously close to the Recombination Case B value, yet the radio flux indicated an optically-thick wind that should yield relatively suppressed Brα emission. And of course the FWHM of the weaker, less opaque Pfγ line was larger than that of Brα. There seemed to be little reason to imagine that a simple accelerating outflow could give rise to the observed line emission from S106IR.

3 The CGS4 observing programme

The commissioning of CGS4 on UKIRT was an opportunity not to miss. Used in echelle mode this instrument currently offers spectral resolutions of either $\sim$40 km s^{-1} or $\sim$20 km s^{-1} depending on the choice of camera, together with great sensitivity. The statistical noise in much of the data to be discussed here is under 1 percent. Comparable resolving powers have been available before – the advances are in the instrumental line profile and the greatly reduced impact of changing weather. In 1991 a programme of reobservation of the well-known massive YSOs using CGS4 with echelle was started. Its aim is to obtain the high quality well-resolved IR line profiles that can at last, through comparison with model predictions, provide the firm constraints on the outflow kinematics and geometry that have hitherto been beyond reach. Full details of the observations and data extraction are to be found in Bunn (1992). To date, observations of seven massive YSOs have been collected. At the time of writing, a paper on S106IR is in press (Drew, Bunn & Hoare 1993) and another bringing together results on the other sources is in the draft stage (Bunn, Hoare & Drew 1994).

It is inevitable that pride of place first goes to observations of S106IR, the exciting source of the bipolar HII region Sh-2 106. This object appears to be one of those rare gifts of nature that is set up to make things easy for us. Unlike other members of the BN-type class, its orientation is believed to be known. It has been shown by Solf & Carsenty (1982), from optical long-slit spectroscopy of the relatively unobscured HII region, that the ionized gas in either lobe is expanding away from the dust bar containing S106IR at 75 km s^{-1} and that the outflow axis lies almost in the plane of the sky ($i \simeq 75^{\circ}$). This allows us to assume our sightline to S106IR lies almost in its equatorial plane. Other useful characteristics include the high contrast of its IR line emission relative to the underlying continuum and the independent constraints upon its ionizing flux that have been derived from optical and radio observations of the HII region (O9 is the favoured spectral type, Staude *et al.* 1982; Bally, Snell & Predmore 1983). For this object, a particularly extensive set of observations were made. The line profiles obtained included Brα, Pfγ, Brγ and HeI 2.058μm.

The data on other, perhaps more typical, members of the class is as yet more limited. For most, Brα and Brγ line profiles have been obtained. Observations made at the lower spectral resolution of $\sim$40 km s^{-1} are not as high quality as those made at $\sim$20 km s^{-1}. The reasons for this are poor weather and incomplete removal of a low amplitude ripple due to the order-sorting CVF used with the echelle.

4 Results

4.1 S106IR

In presenting their observations of S106IR, Garden & Geballe (1986) noted that HeI ($5^{3,1}$G–$4^{3,1}$F) 4.049μm emission could be seen shortward of the Brα line. It was this that prompted us to attempt an observation of the HeI (2^1S–2^1P) 2.058μm transition at $\sim$20 km s^{-1} spectral resolution. To our surprise, the line turned out to be a pure absorption feature on-source (Figure 1). Along the slit away from S106IR, narrow nebular emission associated with the HII region replaces the absorption. The on-source profile is clearly skewed toward negative velocities implying formation in an outflow that is most likely to originate from close to the continuum source. This feature is the most direct spectroscopic evidence to date of the stellar wind apparently demanded by the observed radio spectrum.

The lack of significant emission in the on source HeI 2.058μm line suggests that the He^{+} fraction in the outflow may be small. This is at variance with the observation of HeI emission off-source and indeed with the general excitation of the

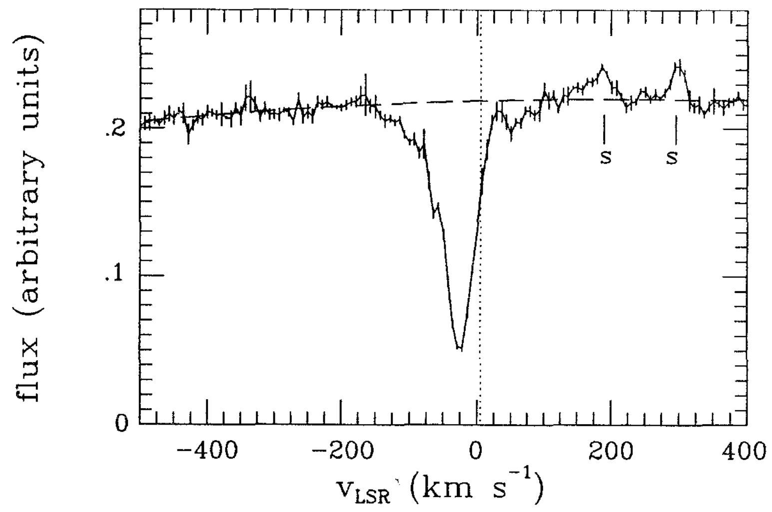

Fig. 1. HeI (2^1S–2^1P) 2.058μm line profile in the spectrum of S106IR. The vertical dotted line marks the systemic velocity of S106IR. The features marked with an 's' are due to uncorrected absorption lines in the standard star spectrum used to remove telluric absorption.

HII region. It seems that the polar and equatorial views of S106IR differ markedly in terms of the apparent ionizing flux.

In section 2, it was noted that it has been found difficult to reconcile the observed HI line profiles with formation in a simple accelerating stellar wind. The new CGS4 data provide a very strong hint as to the cause of the trouble. Earlier observations have for different reasons failed to define the high velocity line wings adequately. Now it is possible to see that the line wings do obey the expected width relation in that the blue wing of Brα extends to higher velocity than it does in Brγ (Brα HWZI = 340$\pm$10 km s^{-1}, Brγ HWZI = 270$\pm$10 km s^{-1}). This is shown in Figure 2 in the form of the Brα/Brγ flux ratio as a function of velocity. The red wings of the two lines are comparable in extent. This can also be reconciled with formation in an accelerating stellar wind: free-free opacity can be significant at $\sim$ 4μm and thus able to erode the red wing of Brα, while it is negligible at $\sim$ 2μm, leaving Brγ intact. Indeed the measured radio flux from S106IR can be used to show that it is quantitatively plausible that the free-free optical depth at $\sim$4μm is about unity (for full details see Drew *et al.* 1993).

It is directly apparent from Figure 2 that the Brα/Brγ flux ratio is much higher in the line core than in the wings and indeed it comes close to the optically-thin nebular recombination Case B value for the best estimate of the reddening ($A_V \sim$ 21: Eiroa, Elsasser & Lahulla 1979). To explain the combination of optically-thick line wings (F(Brα)/F(Brγ) $\sim$ 1) and an optically-thin line core (F(Brα)/F(Brα) $\sim$ 2.7), one must appeal either to decelerating outflow or to the superposition of two physically-distinct components. Given the simple 'windy' appearance of the HeI

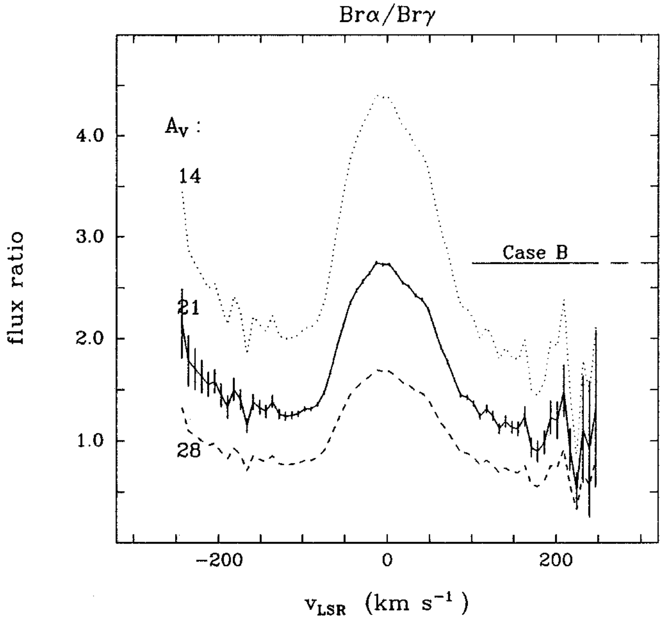

Fig. 2. The Brα/Brγ flux ratio as a function of velocity derived from the spectrum of S106IR. The three curves shown were derived for different reddenings. Eiroa, Elsasser & Lahulla (1979) obtained $A_V = 21$ with a probable uncertainty of ± 5 from far-red and near-IR colour measurements. The expected ratio for Recombination Case B ($\sim$2.7) is also marked. Note that the flux ratio for velocities less than -100 km s^{-1} increases with increasingly negative velocity – as expected for an accelerating stellar wind yielding broader Brα than Brγ.

2.058μm line profile and the existence of the large-scale bipolar flow, the second option is more appealing. The high-velocity HI profile wings are due to the stellar wind, while the bright line cores are produced in a 'nebular' region that is the beginnings of the more sluggish spatially-resolved flow ($v_{\rm exp} \simeq 75$ km s^{-1}, Solf & Carsenty 1982). This allows us to understand why the Brγ FWHM is greater than that of Brα – it is a consequence of the greater fraction of the Brγ flux attributable to the broader stellar wind component (reflecting the fact that the Brackett line decrement is substantially higher for the nebular component than for the optically-thick wind).

The picture of S106IR that emerges from the new data is of an equatorially-flattened wind driven from the vicinity of the IR continuum source ($\dot{M} \gtrsim 2.7\times10^{-6}$ M$_\odot$ yr^{-1} , $v_\infty \gtrsim 340$ km s^{-1}), and a driven HII region expanding at a velocity comparable with that measured from the optically-resolved bipolar flow. Needless to say, this interpretation raises at least as many questions as it has answered. Here there is only space to deal with one of the simplest – is S106IR the only example for which it is necessary to deconvolve the observed HI line spectrum into two physical components?

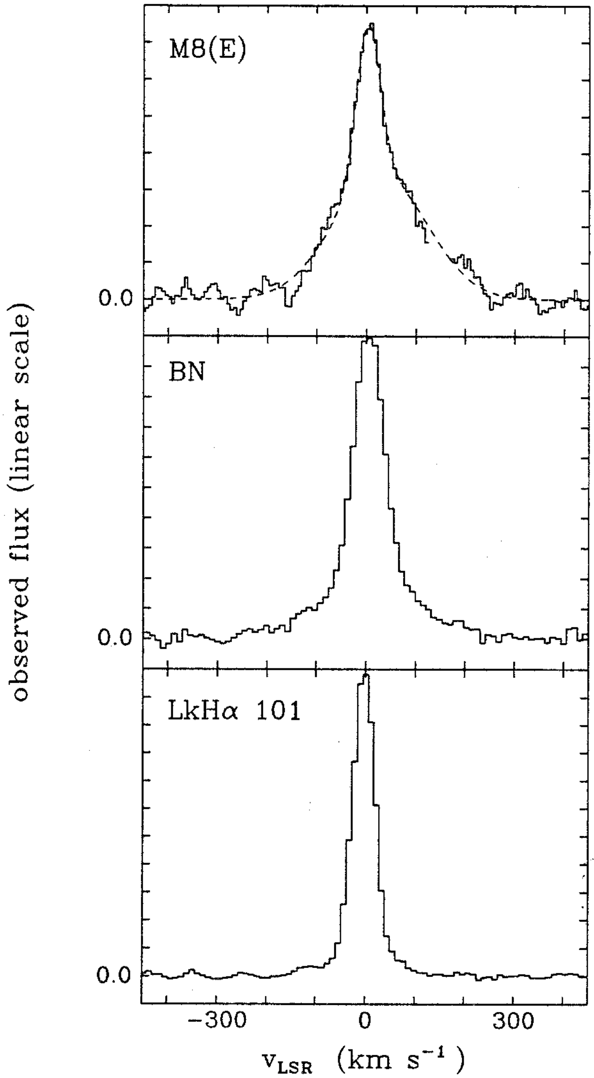

Fig. 3. Observed Brγ line profiles for the sources M8(E), BN and LkHα 101. All were obtained using CGS4 in echelle mode. The spectral resolution is ~20 km s^{-1} for M8(E), and ~40 km s^{-1} for the other two objects. The dashed line superimposed on the M8(E) profile is a multiple gaussian fit included to provide continuity through the gaps caused by deleted telluric features. Note the gradually decreasing contrast of the wing component.

4.2 APPLICATION OF THE TWO-COMPONENT MODEL TO OTHER SOURCES

If it is true that BN-type IR line spectra are composite in the same sense as that of S106IR, we can immediately define two limiting cases. These will be the pure optically-thick stellar wind limit (FWHM[Brα]/FWHM[Brγ] $\geq$ 1), and the opposite extreme of a seemingly unalloyed optically-thin, yet rapidly expanding HII region (FWHM[Brα]/FWHM[Brγ] = 1). Intermediate cases closer to the HII region-dominated limit are the ones for which the line-width ratio will fall below unity, as in S106IR. Of the objects for which CGS4/echelle data have already been obtained, M8(E) provides good examples of line profiles containing an obvious stellar wind component, while LkHα 101 is the most convincing case of an almost pure HII region. To illustrate the trend in profile shape between the limiting cases, Figure 3 contains the Brγ line profiles for M8(E), BN and LkHα 101.

The profiles in Figure 3 can be compared with the data on the Brα and Brγ FWHM measurements set out in Table 1. The quoted line widths have been rounded to the nearest 5 km s^{-1}and may be regarded as no more than 10 percent uncertain. The error in the line width ratio is accordingly no worse than 15 percent. In the absence of a new measurement of Brα in the spectrum of LkHα 101, the measurements of Simon & Cassar (1984, based on 18 km s^{-1}resolution data) are used instead. It is noticeable that where the high velocity line wings are poorly-developed, there is a tendency for the FWHM of Brα to drop below that of Brγ (BN, S106IR, LkHα 101). In these cases we may blame the contrast in Brackett line decrement between the constituent 'stellar wind' and 'HII region' components. In contrast to this, GL 490 and GL 989, resemble M8(E) both in showing well-developed line wings and in yielding FWHM(Brα)/FWHM(Brγ) > 1, as appropriate for line emission dominated by an accelerating outflow.

TABLE I
Measurements of the FWHM of the Brα line and the Brα/Brγ line-width ratio for six BN-type objects

Object name	FWHM(Brα) (km s^{-1})	FWHM(Brα)/FWHM(Brγ)
M8(E)	150	1.5
GL 989	150	1.25
GL 490	120	1.09
BN	70	0.88
S106IR	115	0.77
LkHα 101	38^{+}	0.90^{+}

$^{+}$The figures for LkHα 101 are from the study of Simon & Cassar (1984).

Only one object for which CGS4 echelle data are available at the time of writing is found to challenge this simple decomposition of the HI line profiles into two components. It is M17(SW) IRS1. Even when the Brα and Brγ line profiles are overplotted on an absolute flux scale, the high velocity wings present in the Brγ profile are wider and stronger than in both Brα and Pfγ (3.75μm). Given that the Pfγ wings are *not* wider than the Brα wings, a likely explanation for the greater strength of the wings in Brγ is reflection by dust. In other words, our sightline into M17(SW) IRS1 is not direct. This is a possibility that it is now feasible to examine by means of high spectral resolution spectropolarimetry.

5 Conclusions

The high-quality echelle spectroscopy that can now be performed in the infrared is beginning to allow full use of observations of emission line profiles for the task of extracting the physical and kinematic information they surely contain. From the data gathered so far, it has been argued that the line emission from the spatially-unresolved luminous sources known as BN-type objects is due to a mix of (i) optically-thick stellar wind and (ii) a more slowly moving optically-thin volume of gas that, in some extreme objects can dominate the HI line emissivity. This is not an entirely new idea – Simon & Cassar (1984) pointed out that two distinct regions of HI line emission were needed in order to produce the observed Brγ emission in LkHα 101 (Simon & Cassar 1984). It is the generalisation of the idea, made possible by the great improvement in data quality, that is the step forward.

It is not immediately obvious just what the optically-thin component must be, since the velocity widths seem to be too large to allow identification with conventional HII regions expanding by means of thermal over-pressure. In the case of S106IR, momentum conservation allows that it may be a mass-loaded flow (cf. Hartquist *et al.* 1986) resulting from the percolation of the stellar wind through interstellar debris left over from the star formation process. It also remains unclear just what the stellar wind really is. In S106IR it is equatorially-flattened and, in objects where radio flux measurements provide mass loss rate estimates, it seems the outflow is much denser than is typical of main sequence stars. Could these outflows be fed from a reservoir of marginally-bound material in a circumstellar disk? A troublesome fact in this and some other respects is the failure so far to find any clear spectroscopic signature of rotational motion.

As well as posing new questions, the two-component model offers the prospect of settling a very basic and thorny one – namely, what is the total extinction towards each object individually? It is usually the case that A_V is highly uncertain. Greater certainty would make it possible to apply a much wider range of diagnostic tools in the analysis of these objects. Interestingly, it can be seen from the line flux ratio plot for S106IR (Figure 2) that the hypothesis the narrower core component is optically-thin would indicate an A_V a little in excess of 21. This happens to be in good agreement with a pre-existing estimate based on a continuum method. The precise value implied by Figure 2 depends on how the Brα/Brγ flux ratio in the stellar wind component is interpolated through line centre. This points the way towards an improved technique for determining reddenings: namely, line profile modelling, aimed at defining the likely characteristics of the stellar wind emission near line centre, followed by deconvolution of the observed velocity-dependent Brα/Brγ flux ratio. In practise, this is likely to be a mildly iterative process.

To make progress on these issues, there is much more that can be done both at the telescope and on the office workstation. The new era in the infrared has only just begun. It is an exciting time to return to the study of this most elusive subset of the young stellar population.

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