The Extreme Mass-Loss Signatures of Massive Young Stellar Objects

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Abstract. Infrared spectral observations of embedded young OB stars (the BN-type objects) are briefly reviewed. It is then argued that recent H I emission-line observations have revealed that stellar-wind emission is often mixed with spatially-unresolved circumstellar emission. It nonetheless remains a problem that the outflow velocities measured for these objects are very much lower than those of comparable field OB stars. A new model able to explain this is described: continuing modest accretion onto an embedded luminous young star gives rise to a suitably dense, low-velocity radiation-driven disk wind. It is noted that the disk-wind model may provide the clue to the peculiar phenomenology of B[e] supergiants.

1. Introduction

Star formation has become one of the grand themes of present day astronomy. There is, of course, a natural fascination with the subject in its own right since increased understanding will yield insight into the origins of our own home. There is also a wider astronomical motivation in that a good grasp of the process of star formation is essential to larger-scale issues, such as galaxy formation, and the phenomenology of high-redshift objects. It is within this context, and simply because so little is yet known, that it is appropriate to ask how massive stars form, and how their early evolution differs from that of low-mass stars.

The aim of this contribution is to pick up the thread of work carried out mainly in the 1980s that was concerned with the origin of the apparently enhanced mass loss exhibited by embedded young OB stars. As is described elsewhere in this volume, infrared spectroscopy has only come of age within the past few years. As happened earlier in optical spectroscopy, the introduction of area detectors to infrared (1–5μm) spectroscopy has had a dramatic effect. Data of high quality and high spectral resolution are now a reality. A technological change of this nature is reason enough to revisit an unsolved problem that has fallen into neglect through lack of new data and new inspiration.

The first two parts of this article are a review of the data and the thinking about them. In the last part, two issues are addressed. First, a more generalized interpretation of the IR H I emission-line spectral phenomenology is discussed. Secondly, a new model is proposed for massive young stellar objects, which shows considerable promise of explaining the unexpectedly low-speed, dense outflows associated with them.

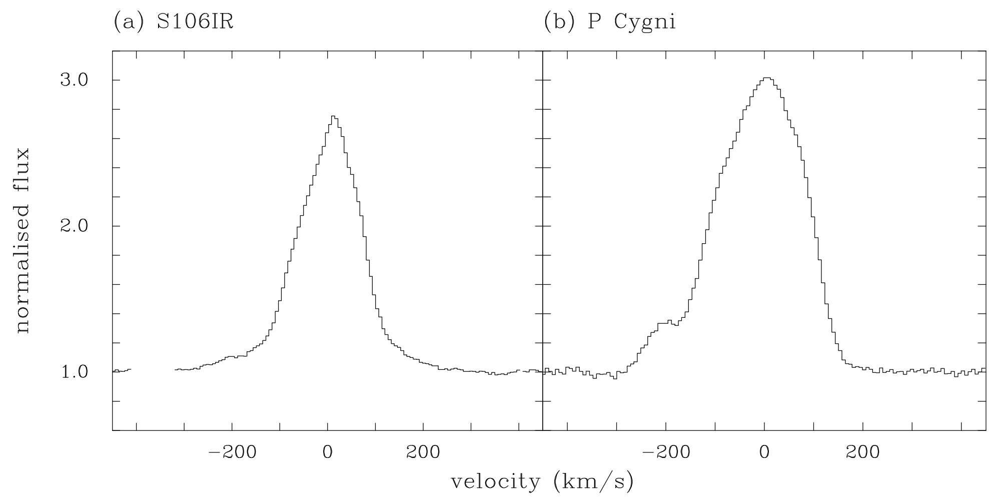

Figure 1. Brγ in the spectrum of (a) the BN-type object S106IR, and (b) P Cyg. Both observations were obtained using the echelle mode of CGS4 at UKIRT.

2. Phenomenology: IR Spectral Distinctions Between Youth and Maturity

It is appropriate to begin with a concise definition of the problem. The relevant phenomenological object classes are the BN-type objects and early Herbig Be (HBe) stars. Their challenge to our thinking rests primarily in their emission-line characteristics: like classical Be stars and, more particularly, the B[e] supergiants, these young, late-O/early-B stars present broad, very-high-contrast H I line emission.

The observed IR H I line emission cannot be reconciled with the expected properties of normal main-sequence stars for two reasons. First of all, the strength of the line emission seems to demand mass-loss rates more than an order of magnitude higher than is consistent with their bolometric luminosities. For example, the results of Simon et al. (1983) for BN-type objects indicate $\dot{M} \simeq 10^{-6}$–$10^{-7} M_{\odot}$ yr^{-1}, at $L \simeq 10^4$ $L_{\odot}$, as compared with $\dot{M} \leq 10^{-8}$ $M_{\odot}$ yr^{-1} for comparable field dwarfs (e.g., Howarth & Prinja 1989). Regrettably, this crucial point has sometimes been glossed over in the YSO literature because of what seems to be a failure to distinguish between supergiant and dwarf mass-loss rates. Secondly, the line widths measured from embedded OB stars do not point toward maximum outflow velocities that are typical of field main-sequence stars of comparable luminosity. FWHM $\simeq$ 100–300 km s^{-1} is characteristic of BN-type objects and Herbig Be stars, while terminal velocities in excess of 1000 km s^{-1} are more the norm for field late-O/early-B stars. These numbers, taken at face value, would seem to suggest that the momentum requirements of the flows from young stars are higher than those of comparable field stars.

These differences are not just an unfortunate byproduct of only being able to access embedded OB stars at infrared wavelengths, while the properties of normal field stars have been deduced from optical and ultraviolet wavelengths. Direct comparisons at IR wavelengths show that the H I line profiles of normal main-sequence OB stars are easily distinguished from those of young objects. For example, at Brγ, it has recently become clear that the most emission to be expected of non-Be O9–B2 V stars is a modest central reversal in the spectra of slowly rotating stars – this is now widely recognized as an non-LTE effect (Murdoch, Drew & Anderson 1994; Zaal et al. 1997). At the same time, Brγ emission in BN-type objects and HBe stars often approaches the level of contrast seen only in B supergiants and similar – the measured IR line widths are also similar. Figure 1 compares Brγ profiles seen in the spectra of S106IR, a much-studied BN-type object, and P Cyg.

Another significant piece of phenomenology is that it is rare for the H I line emission of BN-type objects to appear double-peaked even at high spectral resolution (e.g., Bunn, Hoare & Drew 1995). In this respect BN-type objects are clearly different from classical Be stars. The criteria for classification of HBe stars are somewhat looser than for BN-type objects and are known to occasionally admit probable classical Be stars (e.g., the Class III stars as defined by Hillenbrand et al. 1992). In keeping with this heterogeneity, the optical (and indeed IR) profile shapes of HBe stars are rather more varied in character (Finkenzeller & Mundt 1984). At this point it is worth mentioning the peculiar case of MWC 349A – this object may be young or it could be post main sequence (and hence better viewed as a B[e] supergiant). The Brackett lines and also Fe II emission in this object suggest some rotational splitting (Hamann & Simon 1986). However, at radio wavelengths this object is known, exceptionally, to give rise to H I-line *masing* (e.g., Thum, Martin-Pintado & Bachiller 1992), a fact to return to below.

3. The Historical View

The 1980s saw a burst of modelling and interpretation of observations of BN-type and related objects that in the first instance resulted in outflow models that can be described as supergiant- or even hypergiant-like. In view of the typically high contrast of the H I line emission with respect to the continuum and the modest observed outflow speeds this was an unsurprising development. The emphasis in several studies (e.g., Simon et al. 1983; Höflich & Wehrse 1987; Alonso-Costa & Kwan 1989) was on matching observed line-flux ratios, rather than on understanding the details of line-profile shapes and their possible geometric implications. This was a necessary bias given the data then available. It is the interpretation these simple models place on IR spectral data and radio fluxes that gives rise to the mass-loss rates quoted as typical for the object class.

Even before the advent of IR arrays, the technique of Fourier-transform spectroscopy was applied in certain instances to observe with high enough resolving power at IR wavelengths to spectrally resolve the emission-line profile (e.g., BN, Scoville et al. 1983; LkHα 101, Simon & Cassar 1984; MWC 349A, Hamann & Simon 1986). In parallel with this it began to be appreciated that the spectra of luminous YSOs often include line emission from a cool, nearly neutral component together with the H I tracing hotter ionized gas (McGregor, Persson & Cohen 1984; Geballe & Persson 1987). These results encouraged the view that a cool, dense circumstellar disk might exist in association with a fast ionized wind in these objects. Recent work on the CO 2.3-μm bandhead at echelle resolution (Chandler et al. 1993) has revealed a rotational component of motion that vindicates this basic picture.

However, prompted mainly by the low observed H I emission-line widths, the combination of disk and wind components has become one in which the circumstellar disk is presumed not to extend inwards to reach the stellar surface. In effect, the logic is that 'lower-than-expected' outflow velocity is taken to imply a 'larger-than-expected' radius of origin. In such a configuration, it is not entirely clear what the outflow physics must be. Hamann & Simon (1986), in their discussion of MWC 349A, speak vaguely of ablation of disk material (at a radius of some 5AU). The disk itself serves as the medium responsible for double-peaked Fe II emission detected in MWC 349A. Persson, McGregor & Campbell (1988) present a very similar picture in discussing observations of GL 490 and S106IR (see also Hamann & Persson 1992 on HAeBe stars). To some extent the 'photoevaporation' concept recently proposed by Hollenbach et al. (1994), in which diffuse photons heat the outer part of a circumstellar disk and hence permit a thermal outflow, may be seen as providing the mechanism these earlier studies were groping after. However, it is unlikely that this model can easily explain single-peaked (rather than double-peaked) H I line emission as broad as observed in $L \simeq 10^4 L_\odot$ sources.

4. New Perspectives

4.1. On the Origins of H I Line Emission

While it is true that, on average, the emission in the Brackett lines appears at high contrast in BN-type objects, it is important to recognize that there is considerable variation in contrast from source to source (e.g., Bunn et al. 1995). If this emission is viewed as coming primarily from a spatially-unresolved stellar wind, the range in contrast might be seen as translating into a significant range in mass-loss rate. There is a second sense in which variety, rather than uniformity, is typical of the class. The observations obtained at higher spectral resolution during the 1980s (Persson et al. 1984; Garden & Geballe 1986) revealed instances in which Brγ was found to be narrower than Brα and instances in which the opposite was true. Accelerating outflow is consistent with FWHM(Brγ) $<$ FWHM(Brα), while rotational motion or even deceleration is seemingly required by the opposite inequality.

It is probable that both these effects, the contrast range and the lack of a consistent picture from the relative widths of Brγ and Brα, have a common origin – the H I line emission is often a hybrid of broad, optically thick 'wind' emission and superposed narrow, more nearly optically thin 'nebular' emission. Simon & Cassar (1984) were the first to think in this way; in their study of LkHα 101 they argued that the extremely bright Brackett-line core emission (FWHM $\simeq$ 40 km s^{-1}) is produced in a compact H II region, while the very weak, broad line wings might originate in optically thick outflow. With the benefit of new-generation data of very high quality, Drew, Bunn & Hoare (1993) described the more complex case of S106IR in similar terms. In this source the relative contributions of the 'nebular' and 'wind' components are more evenly balanced than in LkHα 101. This fact combines with the steeper Brackett decrement characteristic of the 'nebular' component to produce the situation in which the FWHM of Brγ is larger than that of Brα. Significantly, the overall line contrast is lower in S106IR than in LkHα 101. At still lower levels of H I line contrast, the broad Brackett lines in the spectra of GL 490 and GL 989 seem to be at the opposite extreme to LkHα 101 in that optically thick wind emission does account for the bulk of the observed line flux (Bunn et al. 1995).

Crudely speaking, it seems that there is a potentially evolutionary trend, in which increasing contrast of IR line emission is accompanied by a switch from broad (FWHM $>$ 200 km s^{-1}), opaque wind emission to narrower (FWHM $\lesssim$ 40 km s^{-1}), optically thin emission more like that which is routinely associated with conventional H II regions. The peculiarity of the H II region, in a case like LkHα 101, is that it is compact and dense ($n_e \gtrsim 10^5$ cm^{-3} is possibly demanded by the observed Fe II emission; Simon & Cassar 1984). At this point, it is interesting to review the nature of the distinction between Herbig Be stars and BN-type objects. LkHα 101 is itself a 'cross-over' object in that it is accepted into both classes. Not only are Herbig Be stars typically less severely reddened than BN-type objects, but so also do they also present much higher-contrast line emission, on average. Viewed in these terms HBe stars may simply be older.

When it is appreciated that the H I line emission from BN-type objects may be a mix of optically thin and optically thick emission, it ceases to be obvious that radio flux measurements can be exploited in the simple way that they have been to yield mass-loss rate estimates. The example of LkHα 101 is again illustrative.

Becker & White (1988) obtained multi-frequency radio data that fit well to the $S_\nu \propto \nu^{0.6}$ form indicative of an r^{-2} density distribution ('mass loss at constant velocity'). Encouraged by this, one may deduce $\dot{M}/v_\infty \simeq 3.4 \times 10^{-8}$ ($M_\odot$ yr^{-1})/(km s^{-1}) from the radio data (see Simon & Cassar 1984). This becomes $\dot{M} \simeq 1.4 \times 10^{-6} M_\odot$ yr^{-1} on adopting $v_\infty = 40$ km s^{-1}. But this flow is *not* the optically thick stellar wind primarily, but the IR-bright H II region. Furthermore, the recent MERLIN data of Hoare et al. (1994) show the radio-emitting material to be clumpy. This last fact probably implies that the deduced mass-loss rate is too high (by an unknown amount). To work back from the mass-loss rate for the 'H II region' flow to the rate in the faster optically thick wind, assumptions have to be made. If spherical symmetry were applicable, which in certain sense it cannot be, and if there were a simple exchange of momentum between a conventional fast wind ($v_\infty \simeq 1500$ km s^{-1}) from the B0.5 star in LkHα 101 and the H II-region flow, then the upper limit on the stellar-wind mass-loss rate would drop to $\sim 4 \times 10^{-8} M_\odot$ yr^{-1}. After a downward correction for clumping it is conceivable that the implied $\dot{M}$ could fall in line with, or below, that expected for a radiation-driven wind from an early-B dwarf.

The morals of this tale are that (*i*) existing mass-loss-rate estimates for BN-type objects cannot always be taken at face value, (*ii*) the momentum requirements of BN-type outflows are not necessarily higher than those of radiation-driven winds from field stars of comparable bolometric luminosity.

4.2. A New Wind Model

As described in Section 3, it is recognized that obscured luminous young stars, like their late-type counterparts, are likely still to be in possession of dense circumstellar disks. At the same time, it is recognized that ionized outflow must also be present in order to explain the observed broad, single-peaked IR H I line emission. However, the response to the modest outflow speeds (100–300 km s^{-1}) implied by the same data has been to suppose that the outflow begins far from the stellar surface. The price for this has been no satisfactory physical model for the outflow to date.

What has not yet been considered is the possibility that the much-talked-of disk is not, typically, detached from the stellar surface and that radiation pressure could power mass loss from the Keplerian reservoir provided by the inner disk. While T Tau stars are undoubtedly too underluminous for radiation pressure to be seriously in contention for driving their outflows, the same is certainly not true for young late-O/early-B stars (where $L/L_{\rm Edd} \gtrsim 0.01$). Indeed a possible distinction between massive YSOs and lower-mass YSOs is that radiation pressure takes over the role in the former that only MHD effects can fulfill in the latter. It is perhaps significant that highly-collimated jets are a phenomenon more obviously associated with lower-luminosity YSOs, rather than with BN-type objects. Certainly, bipolar flows are associated with S106IR and several other high-luminosity YSOs, but in none is the collimation tight enough that the term 'jet' can be applied unambiguously. Effective magnetic-hoop stresses certainly seem to be a requirement for jet production.

Numerical models of radiation-driven disk winds are now available and their general properties have been described by Proga, Stone & Drew (1997). If it is the case that BN-type objects are simply hydrogen-burning late-O/early-B stars, which differ from their field counterparts only in continuing to accrete matter from a circumstellar accretion disk, then it is now technically feasible to begin to ask if radiation pressure, mediated by spectral lines, is able to produce the outflow that observations require.

Suppose that a $10M_\odot$ star continues to accrete at a rate of $10^{-6}M_\odot$ yr^{-1}. Would we know directly from the spectral-energy distribution that the accretion is continuing? In the absence of a reliable, independent measure of reddening, the answer to this question would have to be 'no'. From tables of Rosseland opacities (see also Hartmann, Kenyon & Calvet 1993) one may deduce that an accretion disk characterized by this mass accretion rate would be optically thick. The implication of this is that stellar radiation falling on the inner disk would be absorbed and re-emitted. This reflected component would, in fact, greatly exceed the disk's self-luminosity. Consequently the spectral-energy distribution would, to a first approximation, be modified in the way described by Kenyon & Hartmann (1987): instead of following the Rayleigh-Jeans form, the apparent optical/IR energy distribution would be somewhat flatter (roughly following a $f_\lambda \propto \lambda^{-3}$ shape in the limit of thermalization of the reflected radiation). In evaluating the dynamics of the outflow driven from the disk by radiation pressure, it is important that the light reprocessed by the inner accretion disk is taken into account, as it is in the following.

Using essentially the same 2.5-dimensional numerical methods as are described in Proga et al. (1997), a disk-wind model has been calculated for the case of a star of mass $10M_\odot$, radius $5.5R_\odot$, and luminosity $8500L_\odot$, accreting at a rate of $10^{-6}M_\odot$ yr^{-1} (Drew, Proga & Stone 1997). Presently, the spectral-line force multiplier used is of the simple form $M(t) = kt^{-\alpha}$, where k and α are constants and t is proportional to the local density divided by the relevant velocity gradient (in more than one dimension, this part of the force multiplier is anything but simple – details are given in Proga et al.; see also Owocki, Cranmer & Gayley 1996). Mass is allowed to enter the computational domain through both the stellar and disk 'photospheres'. A steady state is achieved, in which the calculation follows (i) a fast polar wind from the star, (ii) a transitional zone in which the stellar wind experiences some streamline compression due to the presence of the disk flow and the reprocessed disk radiation, (iii) a very much denser, slower equatorial outflow from the disk. Figure 2 shows the model density distribution and velocity field.

The polar wind density and outflow speeds are very much in line with modified CAK theory – without the disk, the total mass-loss rate in the spherically-symmetric wind would be $\sim 10^{-8}M_\odot$ yr^{-1} and v_∞ would be $\sim$2000 km s^{-1}. The mass-loss rate indicated for the model shown, including the disk component, is three times higher. However, the density contrast between the polar wind and the peak of the mass flux at an angle of $\sim 70°$ is about 3 orders of magnitude! Radial velocities in the stream originating from the disk range from 400 km s^{-1} down to zero at the de facto boundary between the disk atmosphere and outflow. The comparison that the measured H I-line FWHM are typically a couple of hundred km s^{-1} or so is very encouraging. Currently, the disk atmosphere scale height towards larger disk radii is undoubtedly exaggerated by the isothermal approximation made in the model. Tests suggest that when this is corrected there is unlikely to be much change in either the mass-loss rate or expansion velocities.

It has been suggested in the past (Lamers & Pauldrach 1991) that an equatorially-enhanced dense, slow wind would be expected, in any case, from a rapidly rotating early-B star because of an ionization sensitivity of the force multiplier that has been termed (possibly a little misleadingly) 'bistability'. In Fig. 2 such an effect is already apparent in the case of a non-rotating star and a uniform force multiplier ($k = 0.3$ and $\alpha = 0.5$ everywhere). Here the slow, dense equatorial flow is a consequence of its being drawn from a Keplerian reservoir (remember that in the disk mid-plane, the effective gravity is zero). 'Bistability' would presumably enhance the contrast between the polar and equatorial flows still further.

The promise of this model is that it provides, in a conceptually simple way, the high-density, slowly expanding outflow that observations seem to require. Although line-profile synthesis is going to be necessary to verify the point, it seems plausible that outflow rather than rotation will dominate the shape of optically thick spectral lines – the rotational component of motion is only dominant within the disk atmosphere and close to the stellar surface. Optically thin lines originating close to the disk plane, perhaps within neutral or, at best, partially-ionized gas, may produce double-peaked line profiles. Very high inclination could also help bring out a spectral rotation signature. It is in this context that it is useful to return to the example of MWC 349A in which, unusually, double-peaked line emission is seen – the hydrogen-line masing and indeed the source's

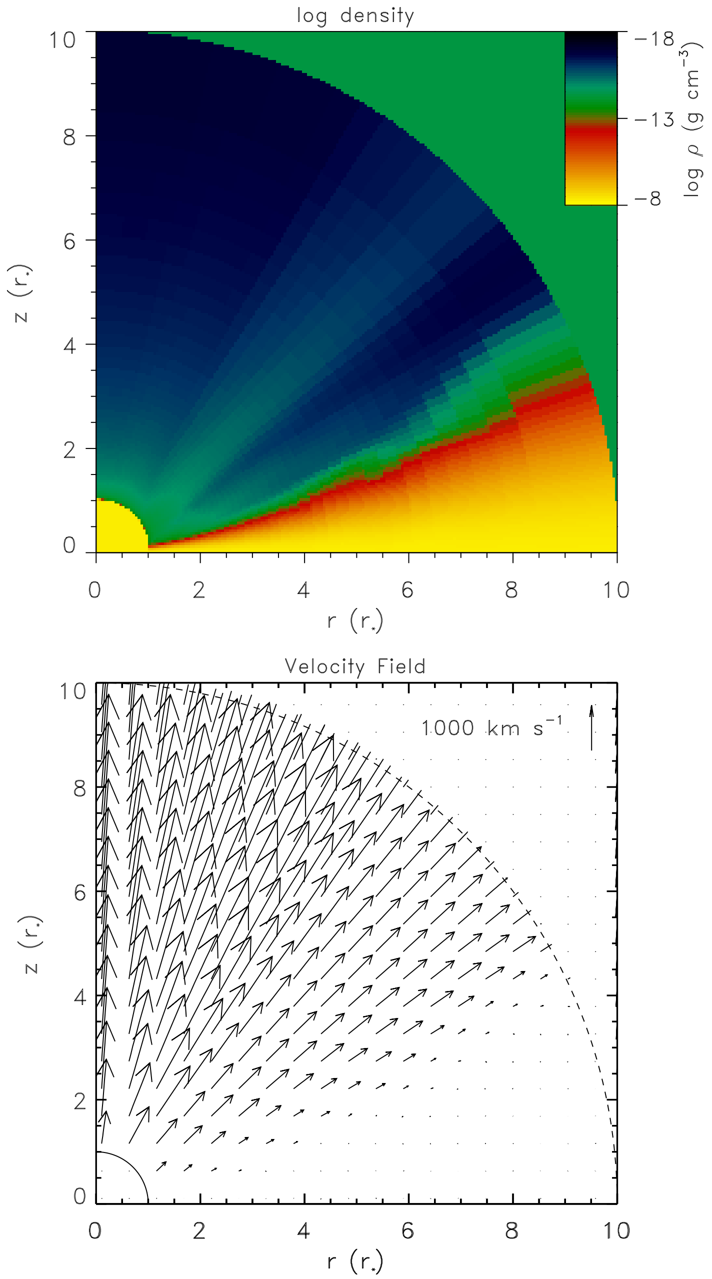

Figure 2. The top panel is a density map of the early-B-star disk-wind model, described in the text. The lower panel is a mapping of the velocity field. Note that the rotation axis of the star is along the left-hand vertical frame, while the mid-plane of the circumstellar accretion star is along the lower horizontal frame.

radio morphology are suggestive of uniquely high inclination (see Strelnitski, Ponomarev & Smith 1996 and references therein).

5. Closing Remarks

The radiation-driven disk-wind model described above serves to illustrate the point that there is a significant difference between driving mass directly from a stellar surface and from a Keplerian orbit close to the stellar surface – even without appealing to 'bistability', one can expect much lower terminal velocities in the latter case. While it is hard to imagine that B[e] supergiants that have evolved well beyond the main-sequence stage are still in possession of accretion disks, it is possible that the morphological parallels between B[e] supergiants on the one hand and BN-type objects and HBe stars on the other have a broadly common origin. Perhaps something like a truncated radiation-driven 'decretion disk' wind model is ultimately what is required to explain the evolved objects. In any event careful consideration will need to be given to the potentially non-spherical character of the radiation field that such a model implies. Applications of the concept of radiative driving continue to multiply!

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Discussion

Owocki: I'd like to ask a little bit more about the actual driving mechanism. The radiation is coming off the disk itself?

Drew: No, the disk luminosity generated by accretion isn't enough by itself to do the trick. We're using a simple algorithm which turns the *stellar* radiation incident on the disk into a reprocessed luminosity, and that, together with the direct stellar radiation, drives the disk wind.

Owocki: Okay... naïvely at least, I'd expect the inner disk to lose mass after a while, just because that's where most of the wind is coming from; is it resupplied?

Drew: Yes, it can be viewed as an active disk in the sense that it has an accretion rate.

Owocki: Then don't you need to match things up pretty nicely at the disk/star boundary?

Drew: No, for the purposes of the simulation it suffices that the disk accretion rate exceeds the disk-wind mass-loss rate by something like two orders of magnitude.

Conti: Janet, you mentioned that high-mass YSOs don't have jets. What's the evidence on that? Or is it a lack of evidence?

Drew: Essentially, lack of evidence – any good jet you care to mention will be associated with a low-mass object...

Hanson: DR21?

Drew: ...with the exception of DR21. [Laughter.] And it's not really certain what the luminosity of that object is. There's also a distinction to be made between a really tightly collimated jet and molecular bipolar outflow; you don't get the former in high-mass objects (with the possible exception of DR21).