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A radiation-driven disk wind model for massive young stellar objects.

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ABSTRACT
A radiation-driven disk wind model is proposed that offers great promise of explaining the extreme mass loss signatures of massive young stellar objects (the BN-type objects and more luminous Herbig Be stars). It is argued that the dense low-velocity winds associated with young late-O/early-B stars would be the consequence of continuing optically-thick accretion onto them. The launch of outflow from a Keplerian disk allows wind speeds of $\sim$200 km s^{-1} that are substantially less than the escape speed from the stellar surface. The star itself is not required to be a rapid rotator. Disk irradiation is taken into account in the hydrodynamical calculation presented, and identified as an important issue both observationally and from the dynamical point of view.

Key words: hydrodynamics – accretion discs – stars:mass-loss – stars: pre-main sequence

1 INTRODUCTION

After the first ground-based IR surveys were carried out and as IR spectroscopy began, it was discovered that some of the most IR-luminous point sources could be associated with optically-invisible stars embedded in giant molecular clouds. The bolometric luminosities of these objects was determined to be consistent with their being young OB stars (Wynn-Williams 1982). Commonly referred to as 'BN-type' objects after the Becklin-Neugebauer source in OMC-I, these stars were subjected to intensive study during the late 1970s and through the 1980s.

A key unsolved problem presented by these objects is the dynamical origin of the bright, and broad HI recombination line emission seen in their spectra. Simon et al. (1983) showed for a number of sources that mass loss rates in excess of 10^{-7} M$_\odot$ yr^{-1}are required if the IR line emission is attributed to a spherically-symmetric wind. Field stars of comparable (late-O, early-B) spectral type only shed mass at a rate of order a few times 10^{-9} M$_\odot$ yr^{-1}(Howarth & Prinja 1989, see also Cassinelli et al. 1994). A further distinction to be made between young embedded OB stars and their field counterparts concerns their terminal wind speeds: in BN-type objects, 100–300 km s^{-1} is measured from the IR lines, whereas velocities in the region of 1500 km s^{-1} are more typical of field main sequence stars (e.g. Prinja, Barlow & Howarth 1990). The low outflow velocities typical of BN-type objects are only emulated in the field by very low surface gravity supergiants. The apparently high mass loss rates and low outflow speeds have never been satisfactorily explained, although it has proved possible to obtain reasonable fits to observed line flux ratios from models of spherically-symmetric mass loss (e.g. Simon et al. 1983, Höflich & Wehrse 1987).

Prompted in part by the need to explain the low observed outflow velocities and in part by a growing acceptance that all young stars pass through a disk accretion phase (e.g. Yorke 1986; Adams, Lada & Shu 1987), observations of BN-type and similar objects began to be interpreted in terms of incomplete disks and fast winds of undefined origin (e.g. Hamann & Simon 1986, Persson, McGregor & Campbell 1988). More recently still, attention has focused on the concept of photoevaporation (Hollenbach et al. 1994) which exploits a combination of heating and ionization by diffuse radiation and, for more luminous exciting stars ($M > 15M_\odot$), wind ram pressure in order to drive matter away from a remnant protostellar disk. The motivation for this work was to identify a means of fuelling compact and UC HII regions for long enough to explain the Galactic HII region statistics of Wood & Churchwell (1989). Significant features of the model are that the main mass loss occurs at tens of AU away from the young star and that the stellar wind itself is normal and, in effect, a boundary condition (see also the similar study by Yorke & Welz 1996). Our aim is to elucidate the flow on this boundary.

We argue there is a simple, physically appealing model for the winds from BN-type and related objects that may yield both the observed IR line widths and the seemingly high mass loss rates required. Specifically, we demonstrate that massive YSOs can readily drive relatively low-velocity, high-density equatorial winds by means of radiation pressure (mediated by line opacity) from Keplerian circumstellar disks that reach into the stellar surface. Indeed, most of the mass is lost from inside $r \sim 2R_*$. A key feature of the model is that drawing mass from an extended Keplerian reservoir breaks the usual link between main sequence high surface gravity and high emergent stellar wind speed. This builds upon recent modelling of radiation-driven disk winds applied successfully, in the first instance, to cataclysmic variable mass loss (Proga, Stone & Drew 1998, hereafter PSD). For the model to have relevance to BN-type objects and the more luminous Herbig Be stars, it is sufficient that accretion via a circumstellar disk continues after young OB stars achieve a near main-sequence configuration.

In Section 2 we set out the premises of the proposed model, and go on in section 3 to present the results of a numerical hydrodynamical calculation. The observational consequences of the model are discussed in section 4.

2 THE CONCEPT

Suppose that massive young OB stars spend some time, after they have acquired a more or less main sequence radius and mass, still accreting through an equatorial disk. What would the system look like? Consider an early B star ($L \sim 10^4$ L$_\odot$, $R \sim 5$ R$_\odot$) continuing to accrete at a rate of 10^{-6} M$_\odot$ yr^{-1} – a rate lying in the range associated with HAeBe stars (Hartmann, Kenyon & Calvet 1993), that also shall be seen to be easily high enough to ensure that the mass inflow more than replenishes the mass lost through outflow. The accretion luminosity in this case would be entirely negligible compared to the stellar luminosity. Figure 1 presents a rough picture of the spectral energy distribution (SED), calculated by assuming that blackbody radiation at the appropriate effective temperature is emitted from all surfaces. The accretion component only starts to modify the SED noticeably at ~ 2 μm.

Although the self-luminosity of the disk is insignificant, it is essential to the model presented here that at the chosen accretion rate, $\dot{\rm M}_{\rm acc} \sim 10^{-6}$ M$_\odot$ yr^{-1}, the disk is likely to be optically-thick (see Hartmann et al. 1993). This means that the stellar radiation falling on the disk will be scattered or absorbed and then re-emitted, thereby changing the overall geometry of the radiation field. The apparent SED will also be altered. First order calculations of this effect were carried out by Kenyon & Hartmann (1987). In Figure 1, we present the result of a calculation like theirs for the case that the disk is geometrically thin and completely flat. We also retain their assumptions that the radiation incident on the disk is completely thermalised and re-radiated isotropically. It may be seen in the figure that the Rayleigh-Jeans tail of the B star's SED is significantly altered by the reprocessed component.

The optically-thick disk's reprocessing of the stellar radiation field has implications both for observation (a point we shall take up again in section 4) and for the outflow dynamics through its effect on the radiation field geometry. Any matter above the disk plane and not so far from the stellar surface may see a significant driving flux of radiation from the disk as well as directly from the star. This of

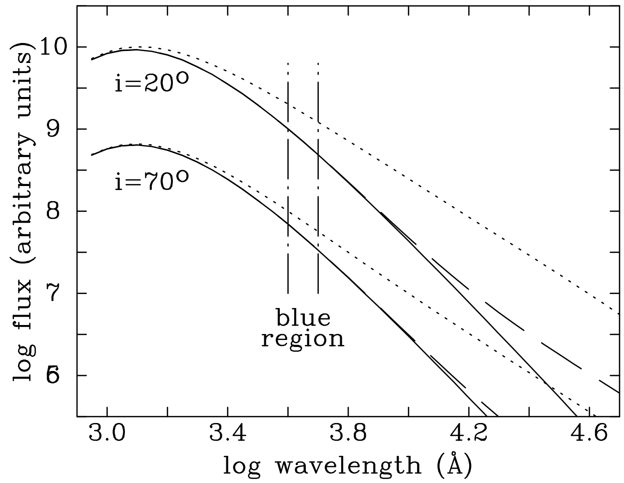

Figure 1. Illustrative spectral energy distributions for a 24000 K main sequence star encircled by an optically-thick accretion disk. Two sets of curves have been calculated: one for a nearly pole-on configuration ($i = 20^o$), and the other for a nearly edge-on view ($i = 70^o$). All surfaces are assumed to radiate isotropically as blackbodies. In each set of curves the solid line represents the stellar photosphere only, the dashed line traces the sum of the stellar photospheric and accretion components, while the dotted line also includes the reprocessed component. The vertical lines mark the blue spectral range normally used to define spectral type. A flat disk has been assumed here. Kenyon & Hartmann (1987) may be consulted for examples of SEDs associated with reprocessing by flared disks.

course requires that radiation pressure is dynamically important. In the immediate vicinity of an early B star, radiation pressure mediated by spectral line opacity can be effective since $L_*/L_{\rm Edd}$ is on the order of 0.01 (for $M \sim$10 M$_\odot$ and $L \sim 10^4$ L$_\odot$), while the opacity presented by plausible ensembles of spectral lines can be up to $\sim 10^3$ times that due to electron scattering alone (Gayley 1995, see also Castor, Abbott & Klein 1975). Hence there is no physical bar to radiation-driven mass loss from a disk around a young early-type star. Here, in modelling this mass loss in the case that the disk is optically-thick, it is assumed that all of the direct and reprocessed starlight is effective in driving outflow (regardless of its spectral characteristics).

The perceived difficulty with radiation-driven mass loss from massive YSOs in the past has been that mass loss direct from the stellar photosphere occurs at too high a velocity and too low a density to make sense of the observations. The problem to tackle is how to raise the wind density and lower the typical outflow speed. The solution is rotation. Friend & Abbott (1986) foretold this in their exploration of one-dimensional radiation-driven wind solutions admitting a rotating stellar surface as the lower boundary . Significantly, their solutions indicated markedly decreasing v_∞ as the rotation on the lower boundary increased. The case we now describe, in which the wind is launched from a reservoir of material in Keplerian orbits (i.e. a circumstellar disk), may be thought of as a continuation of this trend.

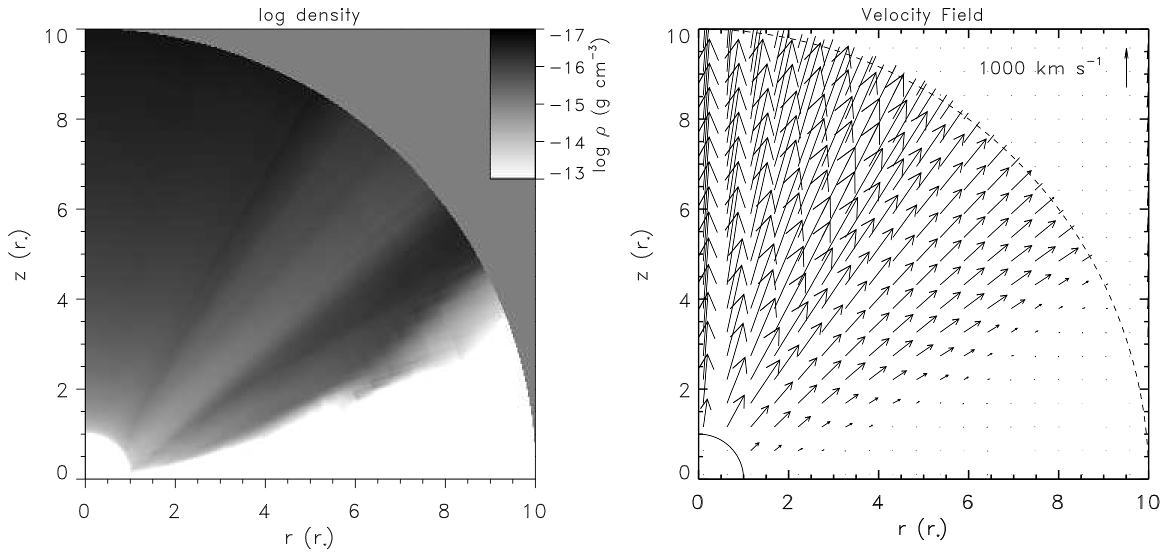

Figure 2. The left hand side panel is a density map of the early B star disk wind model, described in the text. To better illustrate the density changes in the fast outflow in grey scale, an upper cutoff of 10^{-13} g cm^{-3} has been applied (cf. Figure 3). The right hand side panel is a map of the velocity field (the poloidal component only). In both panels 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.

Table 1. Full list of model parameters.

Parameter	Value
M_*	10 $M_\odot$
r_*	5.5 $R_\odot$
L_*	8500 $L_\odot$
c_s	14 km s^{-1}
v_{th}	0.3 c_s
k, α	0.3, 0.5
M_{max}	1000
ρ_0	10^{-8} g cm^{-3}
$\dot{M}_a$	10^{-6} $M_\odot$ yr^{-1}
r_i, r_o	1 r_*, 10 r_*

3 A NUMERICAL DISK WIND MODEL

Our 2.5-dimensional hydrodynamical numerical method is in most respects as described by PSD. However, here, mass is allowed to enter the computational domain from the star as well as from the disk. In order to resolve the subsonic portion of the flow from the star it was necessary to increase the radial grid resolution by using a zone size ratio of 1.08 instead of 1.05 (cf. PSD). The entire domain is sampled by 100×100 points. We consider the case of a non-rotating star of mass 10 $M_\odot$, radius 5.5 $R_\odot$ and luminosity 8500 $L_\odot$, accreting at a rate of 10^{-6} $M_\odot$ yr^{-1}. Note that this implies $L_*/L_{\rm acc} = 300$ ($x = 300$ in the notation of PSD) and hence that reprocessed starlight overwhelmingly dominates the circumstellar disk's light output. The disk is assumed to be flat. A full list of model parameters is given in Table 1.

Our calculation of the radiation force (per unit mass) due to spectral lines at every location in the flow is of the form

$$F^{rad,l} = \int \left(\frac{\sigma_e d\mathcal{F}}{c}\right) M(t). \quad (1)$$

The term in brackets is the electron scattering radiation force and M, the force multiplier, is the increase in the scattering cross section due to line opacity. The integration is over all visible radiating surfaces. Presently, the 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. The complicated interplay between the geometry and flow kinematics demands careful evaluation of the radiation force integral (see PSD). We adopt $k = 0.3$, $\alpha = 0.5$ and impose an upper limit $M_{max} = 10^3$ on the force multiplier. The values picked for k and α have been guided by the literature on line-driving of early B star winds (e.g. de Araújo, de Freitas Pacheco & Petrini 1994; Lamers, Snow & Lindholm 1995). In the early B spectral domain ($T_{eff} \sim 20000$ K), it is known that the radiation force exhibits a 'bistability' in the sense that low Lyman continuum opacity (τ less than a few) yields a more highly ionized medium in which a smaller number of optically-thick lines dominate the force, while higher Lyc opacity produces lower overall ionization and driving by a larger number of optically-thin transitions (Lamers & Pauldrach 1991). In the interests of simplicity, the present parameterisation of the force does not make this distinction but instead uses values of k and α that are intermediate between these two regimes.

Everywhere, we set the sound speed, c_s, to be 14 km s^{-1}, a value that corresponds to T $\sim$ 15000 K, a temperature that is plausible for ionized gas in close proximity to an early B star (see Drew 1989; the precise value of T_{eff} in our model is 23660 K). The sound speed, in combination with the local gravity, determines the pressure scale height

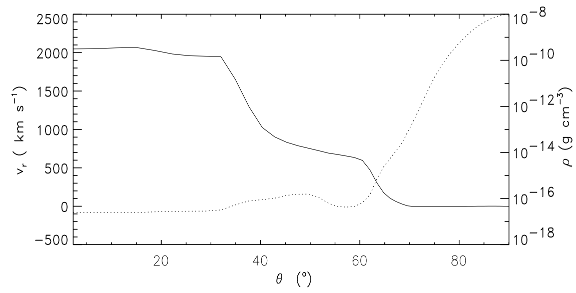

Figure 3. Quantities at the outer boundary in the model from Figure 2. The ordinate on the left hand side is marked by the solid line, while the ordinate on the right hand side is marked by the dotted line.

in the atmospheres of both the star and disk. The boundary density, ρ_0, along the stellar and disk surfaces is constant in time and set to $\rho_0 = 10^{-8}$ g cm^{-3}.

Figure 2 shows the converged model density distribution and velocity field. 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 is exposed to non-radial line-driving due to the reprocessed disk radiation, (iii) a very much denser, slower equatorial outflow from the disk. In the present case, where it has been assumed that the disk is optically thick and reprocesses all incident stellar light into dynamically useful, isotropically re-emitted, light, the surface of the denser, slow equatorial flow lies at $\theta \sim 60^o$ (where θ is the colatitude angle measured with respect to the polar direction).

The polar wind densities and outflow speeds obtaining within the model shown in figure 2 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 the terminal velocity, v_* would be ∼2000 km s^{-1}. The mass loss rate in the model shown is dominated by the disk component and is ∼3 times higher. However, the density contrast between the polar wind and the peak of the mass flux at an angle of $\sim 70^o$ is over two orders of magnitude (see Figure 3)! Radial velocities in the stream leaving the disk range from 400 km s^{-1} down to zero at the de facto boundary between the disk atmosphere and outflow (Figure 3 also). The comparison that the measured HI-line FWHM in BN-type objects and Herbig Be stars are typically a couple of hundred km s^{-1} or so is thus very encouraging. Currently, the disk atmosphere scale height towards larger disk radii is undoubtedly exaggerated by the isothermal approximation made within 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. However the disk component of the wind would very likely be more markedly equatorial than here.

4 IMPLICATIONS OF THE MODEL

The promise of this model is that it provides, in a conceptually simple way, an appropriately high density, slowly expanding outflow. An order of magnitude estimate of the enhancement in the HI line emission measure ($\int n_e^2 dV$) with respect to a normal early-B main sequence stellar wind can be derived. To do this, it is assumed that the normal spherical wind and the disk wind are both uniform within the volumes occupied and that the radial acceleration of both is approximately the same. The scaling then is as:

$$(\frac{\dot{\rm M}_{\rm d}}{\dot{\rm M}_*})^2(\frac{v_*}{v_d})^2(\frac{1}{\cos\theta_d}) \qquad (2)$$

where the subscripts distinguish the normal spherically-symmetric stellar wind from the dense, slow disk wind. Crudely speaking, the angle θ_d is the angle between the 'surface' of the disk outflow and the stellar pole. Inserting the quantities already mentioned above and adopting a typical disk outflow speed of $v_d \sim 200$ km s^{-1}, one obtains an emission measure enhancement in excess of 1000.

Is this enough? The same expression can be used to scale with respect to published HI line models of BN-type objects. For the moment, assume the ratio of velocities is of order unity. The fits to radio and HI line data performed by Simon et al. (1983) and by Höflich & Wehrse (1987) assumed spherical symmetry and constant velocity outflow, and derived mass loss rates within a factor of a few of 5×10^{-7} M$_\odot$ yr^{-1}. Comparison between this mass loss rate and the disk wind mass loss rate obtained here would suggest that up to a factor of 100 in emission measure is still missing. At this point, however, it has to be acknowledged that there are significant complexities in excitation and geometry that the naive scaling fails to quantify. Ahead of synthesising spectral line profiles from the model, it is unclear just what 'representative' disk wind velocity should be adopted in the scaling. HI line emission will undoubtedly be optically-thick (as they are observed to be), which begs the question as to how radiation transfer effects will define the line-forming region. Nevertheless, it is reasonable to anticipate that the disk-like geometry, with its steep latitudinal density gradients, would favour emission from material at a higher mean square density than would a $\sim 1/r^2$ spherically-symmetric density profile.

There is every prospect that outflow rather than rotation will dominate the shape of optically-thick spectral lines. If so, this will fit in with the typically single-peaked appearance of HI line profiles in the spectra of massive YSOs (e.g. Bunn, Hoare & Drew 1995). Since angular momentum conservation will apply, the rotational component of motion is only comparable with the outflow velocities achieved within the disk atmosphere and close to the stellar surface. Only optically-thin lines originating close to the disk plane, perhaps within neutral or at-best partially ionized gas, may produce double-peaked line profiles. For the time being, it is already encouraging that the relatively equatorial configuration we have identified has moved in the direction of the findings of recent high spatial resolution studies of S140 IRS1 and S106IR (Hoare et al. 1994; Hoare, Glindemann & Richichi 1996; Hoare & Muxlow 1996). After the inclusion of an energy balance constraint, in place of the present isothermal approximation, the model outflow is likely to be even more equatorial.

Is the scenario proposed here the only one with a chance of providing a workable equatorial stellar wind model? Until recently there was a prospect that the wind-compressed disk concept of Bjorkman & Cassinelli (1993) would apply to massive YSOs – just as it might apply to B[e] and classical Be stars. Within the last year or so Owocki, Cranmer & Gayley (1996) have shown that the detailed velocity-field dependence of the radiation force inhibits the equatorial focusing of the flow envisaged by the model. Even before the wind compressed disk model appeared, it had been proposed that 'bistability' (Lamers & Pauldrach 1991) would, in the case of rapidly rotating stars, induce a dense, slow equatorial wind in combination with a fast low-density polar wind. Our model achieves a density contrast of up to two orders of magnitude, even in the case of a negligibly-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 gas in orbit around the star rather than from the star's surface. 'Bistability', if it were also accounted for in the disk wind model, may enhance the density contrast between the polar and equatorial flows a little further – for $L_*/L_{\rm Edd} \sim 0.01$, the scaling formula given by Owocki (1997) limits this factor to about 3.

A significant element in our model is the irradiation of the optically-thick circumstellar disk by the star (Figure 1). Our simple model of the SED predicts that direct starlight and the reprocessed component should be comparable in the blue part of the spectrum, while the latter dominates longward of 1μm. The hotter direct stellar component only takes over towards its Planck maximum in the ultraviolet. Since a relatively large fraction of the optical light may be attributable to the disk, heavy element absorption due to the stellar photosphere could prove to be hard to detect. The disk itself will at best contribute rotationally-smeared, weaker line absorption or may indeed produce only line emission (given that the run of temperature vertically within the disk induced by the strong external irradiation will be inverted; see Hubeny 1990). Detailed theoretical models have yet to be constructed and so we should consider what can be learned from the observations that, only now, are beginning to be gathered, Recent repeat observations (Oudmaijer et al. in preparation) of the young B1.5 star, MWC 297, have revealed changes in the B-band heavy element absorption lines with respect to previous observations (Drew et al. 1997) that show they are not simply photospheric. In a study of young stars in M17, Hanson, Howarth & Conti (1997) failed altogether to detect any heavy-element photospheric features between 4100Å and 4800Å in their putative early B stars. The first evidence therefore supports the idea that the optical spectra of high mass YSOs are veiled.

Finally, we turn to the larger context of this work. There can be a fundamental physical distinction between massive and lower mass YSO winds: radiation pressure may take the role in driving mass loss from the former that only MHD effects can assume in the latter. It is perhaps significant that highly-collimated jets are a phenomenon more obviously associated with lower luminosity YSOs, than with BN-type objects. Certainly, molecular bipolar flows are associated with S106IR and several other high luminosity YSOs, but there are no compelling examples of the ionized tight jets to compare with e.g. the HH 34 system (see Bally 1997). It is generally believed that such extreme collimation requires effective magnetic hoop stresses (see the review by Königl & Ruden 1993, but cf. Mellema & Frank 1998). The angular-momentum conserving equatorial wind that we have proposed here does not favour the growth of the necessary toroidal magnetic field. Nevertheless, it would be premature to suggest that magnetic fields have no role to play in young massive stars. That remains to be seen. Our contention here is that radiation pressure must have a role and that now it is possible to describe its action in an axially-symmetric context that suggests a promising model for these objects.

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