Two-dimensional Monte Carlo simulations of HⅠ line formation in massive young stellar object disc winds

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ABSTRACT
Massive young stellar objects (YSOs) are powerful infrared HⅠ line emitters. It has been suggested that these lines form in an outflow from a disc surrounding the YSO. Here, new two-dimensional Monte Carlo radiative transfer calculations are described which test this hypothesis. Infrared spectra are synthesized for a YSO disc wind model based on earlier hydrodynamical calculations. The model spectra are in qualitative agreement with the observed spectra from massive YSOs, and therefore provide support for a disc wind explanation for the HⅠ lines. However, there are some significant differences: the models tend to overpredict the B/Br ratio of equivalent widths and produce line profiles which are slightly too broad and, in contrast to typical observations, are double-peaked. The interpretation of these differences within the context of the disc wind picture and suggestions for their resolution via modifications to the assumed disc and outflow structure are discussed.

Keywords: radiative transfer – methods: numerical – stars: early-type – stars: winds, outflows,

1 INTRODUCTION
Understanding the formation and pre-main-sequence evolution of massive stars (M ≳ 10 M⊙) is an important goal in modern astrophysics. Currently, the formation of low-mass stars via gravitational collapse of a molecular cloud and subsequent disc accretion is, at least conceptually, well understood. However, it is not clear whether massive stars form through a scaled-up version of the same process or whether more complex, environmental effects are important (see, for example, Bonnell, Vine & Bate 2004, for a recent discussion).

Because massive stars form inside dense molecular clouds, they are observed primarily at infrared (IR) and longer wavelengths. Embedded massive young stellar objects (YSOs) are powerful sources of IR HⅠ line emission (Simon et al. 1981, 1983; Drew, Bunn & Hoare 1993; Bunn, Hoare & Drew 1995; Blum et al. 2004) with equivalent widths (EWs) in Br of ~5–90 ˚Å (Bunn et al. 1995). The lines profiles are complex, displaying both fairly narrow (FWHM ~50–100 km s⁻¹) line cores and broad wings extending out to ~400 km s⁻¹ in extreme cases. In the sample of objects observed by Bunn et al. (1995), the profiles were always single-peaked but recent observations reported by Blum et al. (2004) include at least one object (NGC 3576) which shows clear evidence of double-peaked profiles. By examining flux ratios across the profiles of lines with differing opacities, Bunn et al. (1995) found evidence that, at least in some sources, the lines form in an accelerating outflow.

Normal, main-sequence OB stars also show HⅠ emission lines. These are produced in the star’s fast (~1000 km s⁻¹) spherical wind, but the strength of emission in YSO spectra is much greater than in O stars. If the features in YSOs were due to reprocessing of radiation in a spherically symmetric wind, the implied mass-loss rates would be up to 10⁻⁸ M⊙ yr⁻¹ (Simon et al. 1983), substantially exceeding those of field stars of comparable spectral type. Therefore, to interpret the HⅠ observations it is worthwhile to consider alternatives to formation in a spherically symmetric structure.

Important observational constraints on the geometry of emitting material in YSOs are provided by the first overtone bands of CO at 2.3 µm (e.g. Carr 1989; Carr et al. 1993; Chandler et al. 1993; Chandler, Carlstrom & Scoville 1995). In particular, both Carr et al. (1993) and Chandler et al. (1995) conclude that models based on an accretion disc surrounding the central object reproduce the CO observations of YSOs. Furthermore, although there are some cases in which CO data can be modelled in terms of a stellar wind, in general the disc model encounters fewer difficulties (see Chandler et al. 1995). The observations strongly suggest that the CO emission originates close to the central star; Bik & Thi (2004) and Blum et al. (2004) have recently studied CO emission from a range of massive YSOs and derived disc radii in the range 0.1–5 au. Thus, it seems probable that YSOs harbour accretion discs containing significant amounts of hot gas fairly close to the central object and it is natural to consider whether the HⅠ emission is associated with such a disc or its environment.

Hamann & Simon (1986) suggested that powerful recombination line emission of the sort discussed above originates in an outflow
associated not with a stellar wind but with mass loss from a disc. Their work focused on MWC 349, an object whose evolutionary status is unclear but which possesses spectroscopic signatures (including H i and CO emission features) broadly similar to the embedded massive YSOs (see Hamann & Simon 1986; Kraus et al. 2000). Hollenbach et al. (1994) developed a model for outflow from young massive stars by photoevaporation of the outer regions of their discs. They were motivated by the need to explain the high frequency of occurrence of ultracompact H ii regions – photoevaporation can provide a source of mass input for H ii regions to balance the loss by pressure-driven expansion. Although the rate of mass loss in photoevaporation models is large, it occurs at large radii (typically > 100 au) and the characteristic flow velocities are low (comparable to the typical sound speed of 10–50 km s$^{-1}$; Hollenbach et al. 1994). Thus, such a flow does not provide a promising origin for relatively high-velocity features, such as the IR H i broad-line wings (Bunn et al. 1995).

Recently, Drew, Proga & Stone (1998) proposed that the intense radiation field produced by a massive YSO may drive mass loss from the surface of the inner parts of its disc. They performed a hydrodynamical simulation which showed that, in addition to driving a normal hot star wind component, radiation pressure from a massive YSO could propel a dense equatorial flow from a surrounding disc with terminal velocity in the same regime as the observed H i linewidths. These results led them to speculate that such a model accounts for the IR H i lines. However, they did not perform the radiative transfer calculations required to confirm this conjecture.

To investigate the possibility that massive YSOs harbour disc winds which give rise to the observed IR H i line emission, in this paper we present the results of new two-dimensional radiative transfer calculations which account for both the complex geometry of a YSO disc wind (starting from, but not limited to, the Drew et al. 1998 model) and the detailed atomic physics of H i line formation.

In Section 2, we discuss the YSO model adopted in this investigation and its parameters. The radiative transfer calculations have been performed using the Monte Carlo (MC) code described by Long & Knigge (2002) after incorporating a sophisticated treatment of H i line formation using the approach described by Lucy (2002, 2003); the method of calculation and code used are discussed in Section 3. Results are presented in Section 4 and our conclusions discussed in Section 5.

2 MODEL

For the radiative transfer calculations (Section 4) we adopt a simply parametrized model for the YSO and its disc. In choosing the parameters for this model, our starting point has been to construct a reasonable representation of the disc wind obtained in the hydrodynamical simulations presented by Drew et al. (1998). Therefore, before discussing our model in detail, a brief description of this hydrodynamical model is given.

2.1 Summary of the hydrodynamical disc wind model

Following the methods of Proga, Stone & Drew (1998), Drew et al. (1998) performed a hydrodynamical simulation of a radiatively driven wind from a disc around a massive YSO. They considered an early-B type star (mass $M_* = 10 \, M_\odot$, luminosity $L_* = 8500 \, L_\odot$, radius $r_* = 5.5 \, R_\odot$) surrounded by an accretion disc extending from the stellar surface to an outer radius $r_{\text{disc}} = 10 \, r_*$, the outer boundary of their computational domain. Noting that, for reasonable accretion rates ($\sim 10^{-9} \, M_\odot \, \text{yr}^{-1}$), the luminosity of the central star far exceeds the accretion luminosity of the disc, they accounted for reprocessing of stellar light by the disc and then computed the radiation force using the Castor, Abbott & Klein (1975) parametrization of the force due to spectral lines.

Their simulation exhibited a steady-state solution with two fairly distinct outflow components: a fast ($\sim 2000 \, \text{km s}^{-1}$) polar wind from the central star, rather similar to a normal hot star wind; and a slower ($\lesssim 400 \, \text{km s}^{-1}$), denser equatorial outflow from the disc at colatitude $\theta \sim 60^\circ$ with mass-loss rate $\sim 3 \times 10^{-9} \, M_\odot \, \text{yr}^{-1}$. Between these two outflow components they found a complex transitional zone in which the stellar wind streamlines were compressed due to non-radial radiation force components and the presence of the disc wind.

Drew et al. (1998) suggested that the high density and moderate velocity of the equatorial disc wind component make it a promising site for the formation of the H i lines observed in massive YSO spectra – our goal is to present radiative transfer calculations to examine this hypothesis.

2.2 Geometry

Fig. 1 illustrates the geometrical construction used to describe the wind, parameters for which are discussed in the next subsection. In order to capture the essence of the Drew et al. (1998) hydrodynamical disc wind model (described above), the structure consists of the following four basic elements.

(i) A central star. The star is assumed to be spherical with radius $r_*$.

(ii) An accretion disc. The disc lies in the $xy$-plane of the adopted coordinate system and is assumed to extend from the surface of the star to an outer radius $r_{\text{disc}}$. For simplicity, it is assumed to be geometrically thin and flat.

(iii) A disc wind. The wind, which is launched from the disc, is described following Long & Knigge (2002) and Knigge, Woods & Drew (1995); namely, the streamlines of the disc wind are assumed to converge at a point which lies on the $z$-axis a distance $d$ below the coordinate origin. Thus, the angular boundaries of the disc wind are...
determined by the choice of the inner and outer disc radii and the distance \( d \): namely, \( \theta_{\text{min}} = \tan^{-1} \left( r_s/d \right) \) and \( \theta_{\text{max}} = \tan^{-1} \left( r_{\text{disc}}/d \right) \) (see Fig. 1). Motivated by the Drew et al. (1998) simulation, the flow is assumed to be stationary and smooth.

(iv) A spherical stellar wind component. This is assumed to occupy the entire polar region above the disc wind and to have radial streamlines. The boundary between the stellar wind and disc wind is not treated in detail; it is assumed to be perfectly sharp. Thus, the transition zone between the disc and stellar winds which exists in the Drew et al. (1998) simulation is neglected here.

2.3 Model parameters

Table 1 gives a list of the wind parameters adopted for the reference model (hereafter, model A) which are discussed individually below. Of our models, model A and the closely related model B (see Section 4.3) are those most closely matching the Drew et al. (1998) simulation.

2.3.1 Central star

The parameters of the central star are those of a B1–B2 main-sequence star. The effective temperature was computed from the luminosity using the Stefan–Boltzmann equation. The star is assumed to emit radiation as a blackbody.

2.3.2 Accretion disc

In our reference model, \( r_{\text{disc}} = 10 r_s \) is adopted – the same computational domain considered by Drew et al. (1998). Realistically, the discs around massive YSOs are likely to extend to significantly larger radii. Therefore, we also consider discs extending to \( r_{\text{disc}} = 100 r_s \) in Section 4. To consider even larger radii becomes impractical because increasing the physical size of the calculation limits the spatial resolution available in the inner regions – computing feasibility prevents us from having arbitrarily many grid cells. It is noted that, at least for the treatment of disc radiation adopted in our reference model, considering an even larger outer radius will have negligible effect; the disc temperature at such large radii will be too low for its thermal radiation to contribute significantly to the IR spectral range under consideration.

Given that it lies considerably beyond the scope of this investigation to study radiative transfer within the accretion disc in detail, approximations must be made regarding the treatment of the disc and its emission. In the calculations presented in Section 4, results using two different approaches are considered. It is known from observations (Henning, Pfau & Altenhoff 1990) that there are significant differences in the IR spectral energy distributions (SEDs) of massive YSOs – some have large near-IR excesses while other have little or no excess. Therefore, we have chosen our two models for disc emission to approximately bracket the range of plausible IR SEDs for massive YSOs.

In some cases, referred to as a ‘reflecting’ disc, it is assumed that the disc effective temperature is determined as a function of radius by the accretion rate (exactly as discussed by Long & Knigge 2002) and that annuli emit as blackbodies at the local temperature. During the MC simulations, it is assumed that any radiation which strikes the disc from above is reflected by a hot disc atmosphere rather than absorbed and reprocessed. Because the computational domain is symmetric about the disc plane, this is closely equivalent to the assumption that the disc is completely optically thin (transparent). In model A, the disc is assumed to be ‘reflecting’.

Alternatively, as a simple ‘reprocessing’ disc model, it is assumed that stellar radiation falling on the disc is absorbed and the energy reradiated. In this case, the disc is divided into concentric annuli and the energy falling on each annulus from the star computed following the discussion of Proga, Stone & Drew (1999). By assuming that all this energy is reradiated locally, and that the annuli radiate as blackbodies, the disc temperatures are then obtained. The accretion luminosity is still included in this model but is small relative to the reprocessed luminosity. At the start of the MC simulation, the disc annuli emit blackbody radiation according to their effective temperatures – thereby accounting for the luminosity due to reprocessing of stellar light – and during the subsequent propagation of MC quanta, any radiation which strikes the disc is simply absorbed.

Computed disc temperatures for both reflecting and reprocessing discs are shown, as a function of radius, in Fig. 2. SEDs for radiant

| Parameter | Value | Varied |
|-----------|-------|--------|
| Central star | | |
| Mass, \( M_s \) | \( 10 M_\odot \) | | |
| Radius, \( r_s \) | \( 5.5 R_\odot \) | | |
| Luminosity, \( L_s \) | \( 8500 L_\odot \) | | |
| Temperature, \( T_{\text{eff}} \) | \( 2.37 \times 10^5 K \) | | |
| Accretion disc | | |
| Inner radius, \( r_{\text{in}} \) | \( r_s \) | √ |
| Outer radius, \( r_{\text{disc}} \) | \( 10 r_s \) | √ |
| Accretion rate, \( \dot{M}_{\text{acc}} \) | \( 10^{-6} M_\odot \text{yr}^{-1} \) | | |
| Disc wind | | |
| Focus point, \( d \) | \( 0.14 r_s \) | √ |
| Mass-loss rate, \( \dot{M} \) | \( 3 \times 10^{-8} M_\odot \text{yr}^{-1} \) | | |
| Mass-loading exponent, \( \alpha \) | 1 | | |
| Terminal velocity, \( v_\infty \) | \( v_{\text{esc}} \) | | |
| Acceleration length, \( R_d \) | \( r_s \) | | |
| Acceleration exponent, \( \beta_d \) | 1.5 | | |
| Stellar wind | | |
| Mass-loss rate, \( \dot{M}_s \) | \( 10^{-8} M_\odot \text{yr}^{-1} \) | | |
| Terminal velocity, \( v_\infty \) | \( 2000 \text{ km s}^{-1} \) | | |
| Launch velocity, \( v_c \) | \( 10^{-2} v_\infty \) | | |
| Acceleration exponent, \( \beta_s \) | 1 | | |

Figure 2. The disc temperature \( (T_{\text{disc}}) \) as a function of radius \( (r) \) for a reflecting disc (solid line) and a reprocessing disc (dashed line). The reflecting disc temperatures are always lower because they only describe the accretion luminosity while the reprocessing disc also accounts for reradiation of energy absorbed from the star.
energy emitted from models with both reflecting and reprocessing discs are shown in Fig. 3. Comparing the SEDs for reflecting and reprocessing discs with $r_{\text{disc}} = 10 \, r_*$ (left-hand panels in Fig. 3) shows that the treatment of the disc makes a significant difference to the continuum brightness in the IR region of interest. If the disc only reflects (or transmits) light which strikes it, the $\sim 2-4 \, \mu m$ continuum is a combination of stellar radiation and accretion luminosity released in the disc (Fig. 3, upper left-hand panel). However, if the disc thermally reprocesses all the stellar light which strikes it, the reprocessed light is dominant (lower left-hand panel). Increasing the outer radius of the disc to $100 \, r_*$ increases its brightness. With a reflecting disc, this effect is fairly small below about $4 \, \mu m$ (upper right-hand panel) because the temperatures of the outer parts of the disc are very low. However, because the reprocessing disc has higher temperatures (Fig. 2), changing its outer radius has a greater effect in the waveband of interest (Fig. 3, lower right-hand panel).

We note that because the treatment of the radiation force is grey in the Drew et al. (1998) simulation and that in both our approaches to the disc SED all the radiative flux which falls on the disc is re-emitted locally, both our disc SED models are equally valid in the context of the hydrodynamical calculations.

2.3.3 Disc wind

The geometry of the disc wind is specified by the distance between the origin and the focus point, $d$ (see Fig. 1). Here, $d = 0.14 \, r_*$ is adopted leading to $\theta_{\text{min}} = 82^\circ$ and $\theta_{\text{max}} = 89^\circ$ (see above). The dense disc wind component present in the hydrodynamical model of Drew et al. (1998) occupied a rather wider angular range ($\sim 25^\circ$). However, Proga et al. (1999) have shown that improved treatment of the radiative line force leads to significantly more swept back equatorial disc winds. In particular, for a model in which the luminosity of the central object substantially exceeds that of the disc (their model E) they found a disc wind with opening angle $8^\circ$. Thus, the $d$ value adopted here is chosen to reflect the narrow disc winds obtained by Proga et al. (1999).

The density and velocity structure of the disc wind closely follows that adopted by Long & Knigge (2002). Following equation (7) of Long & Knigge (2002), it is assumed that the mass-loss rate per unit area from the disc can be described by

$$\frac{\delta M}{\delta A} \propto T_{\text{disc}}(r)^{\alpha_{\text{u}}}.$$  (1)

On the assumption that the mass-loading is proportional to the local luminous flux, $\alpha = 1$ is adopted here. The total mass-loss rate in the disc wind is fixed at the mass-loss rate obtained by Drew et al. (1998): $M = 3 \times 10^{-4} \, M_\odot \, \text{yr}^{-1}$. Note that the improved treatment of the line force (i.e. Proga et al. 1999) did not significantly change the total mass-loss rates from those of the earlier treatment. The poloidal velocity on a streamline in the disc wind is described using equation (8) of Long & Knigge (2002), namely

$$v(l) = c_s + (v_\infty - c_s) \left(1 - \frac{R_d}{l + R_d}\right)^{\beta_d}$$  (2)

where $c_s$ is the sound speed on the disc surface at the base of the streamline, $v_\infty$ is the terminal velocity of the streamline, $l$ is the poloidal distance, $R_d$ is a velocity-law scalelength for the disc wind and $\beta_d$ is an exponent which determines the acceleration of the wind. For simplicity, $v_\infty = v_{esc}$ is adopted where $v_{esc}$ is the escape velocity on the disc surface at the base of the streamline. Fig. 4 shows $v_\infty$ as a function of $\theta$ – these values compare favourably with the terminal

Figure 4. The disc wind terminal velocity ($v_\infty$) versus $\theta = \tan^{-1}(r/d)$ where $r$ is the disc radius at the base of the streamline.

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velocities found by Drew et al. (1998, their fig. 3). To describe the acceleration of the wind, a velocity scalelength for the disc wind, \( R_d = r_* \) and exponent \( \beta_d = 1.5 \) are used.

### 2.3.4 Stellar wind

The density of the stellar wind component is chosen such that it would have mass-loss rate \( \dot{M}_*=10^{-6} M_\odot \text{ yr}^{-1} \) if it were spherically symmetric. Following, for example, Lucy & Abbott (1993), the velocity in this component is assumed to be radial and given by

\[
v = v_c + (v_{\infty} - v_c) \left[ 1 - (r_*/r) \right]^\beta_c.
\]

Based on the Drew et al. (1998) simulations, \( v_{\infty} = 2000 \text{ km s}^{-1} \) is adopted. In addition, \( v_c = 10^{-2} v_{\infty} \) is assumed and \( \beta_c = 1 - \alpha \), where \( \alpha \) is a standard value in modelling hot star winds – is chosen.

### 2.3.5 Departures from the reference model parameters

In Section 4, we investigate the dependence of the results on several of the important model parameters listed in Table 1. The calculation is, of course, particularly sensitive to the choice of density in the wind. The density, in turn, is sensitive to many of the model parameters – most fundamentally, the mass-loss rates which determine the mass-loading of the stellar and disc winds. However, the velocity-law parameters (e.g. \( v_{\infty}, R_d \) and \( \beta_d \)) also play a significant role, as does the geometry of the disc wind (determined by \( \rho_d \)). In Section 4, models with density higher than that in model A will be considered. These are created by increasing the mass-loss rate only – physically this is the parameter which leads to a simple increase in density everywhere in the wind – but it should be noted that there is a degree of degeneracy between this and the other parameters mentioned above.

The second departure from the reference model (model A) that will be discussed in Section 4 is an increase in the outer disc radius, \( r_{\text{max}} \). The relevance of this parameter to the determination of the disc SED has already been discussed (see Section 2.3.2 and Fig. 3).

Finally, a model in which an inner hole is introduced to the accretion disc will be considered. In addition to increasing \( r_{\text{in}} \) for this model, the \( d \) value is changed in order to preserve the same opening angles (\( \theta_{\text{min}} \) and \( \theta_{\text{max}} \)) for the disc wind.

Departures of the other parameters from their reference values will not be considered here. For this investigation we wish to restrict ourselves to central objects with parameters suitable for early-type near-main-sequence stars; thus, we do not consider models with large values of \( r_\ast \). An increase in the stellar radius, \( r_\ast \), would mimic many of the effects associated with the introduction of an inner hole to the disc because both push the wind out to regions where the rotational velocity is lower. Thus, our model with an inner hole can be regarded as a proxy for some of the most important consequences of an enlarged central star.

An increase in the stellar luminosity would clearly affect the SED, but could also change the mass-loss rate and possibly the wind geometry; further hydrodynamical calculations would be required to fully investigate results for a range of luminosities. The mass-accretion rate \( \dot{M}_{\text{acc}} \) is relevant only to calculations with reflecting discs. In such cases, \( \dot{M}_{\text{acc}} \) plays an important role in determining the disc temperature and IR SED. For reprocessing discs, these are controlled by the stellar radiation field and \( \dot{M}_{\text{acc}} \) plays only a minor role. It is very difficult to reliably obtain \( \dot{M}_{\text{acc}} \) by observation or theory and so we restrict ourselves to considering only one value, that used by Drew et al. (1998).

### 2.4 Atomic data

For simplicity, it is assumed that both the disc wind and stellar wind consist entirely of hydrogen. An atomic model with energy levels for principle quantum number \( n = 1–20 \) and the continuum state is used in the calculations. Bound–bound oscillator strengths are taken from Menzel & Pekeris (1935). Bound–bound collision rates are derived from the oscillator strengths using the van Regemorter (1962) formula. Photoionization rates are taken from TOPBASE (Cunto et al. 1993) and collisional ionization rates are computed using equation (5-79) from Mihalas (1978). In addition to these processes associated with atomic hydrogen, free–free absorption and emission by \( \text{H}^+ \) ions and Thompson scattering by free electrons are included in the calculations. All other processes are neglected.

### 3 METHOD OF CALCULATION

In the disc wind model, the IR \( \text{H}^\prime \) line formation is expected to be driven by recombination of ionized hydrogen gas fairly close to the central star. The observed line ratios (e.g. Bunn et al. 1995) indicate, however, that the line emission is not optically thin, making it necessary to perform detailed non-local thermodynamic equilibrium (NLTE) radiative transfer calculations to reliably model the line formation process.

The radiative transfer calculations discussed in the next section were performed using a modified version of the MC code written by Long & Knigge (2002). Because the code has been described in detail elsewhere, only a brief overview and discussion of the important modifications made for this investigation are presented here (see Long & Knigge 2002, for further details of the code).

To synthesize spectra, the code performs a sequence of MC radiative transfer calculations. The code uses indivisible energy packets as the elementary MC quanta, assumes radiative, statistical and thermal equilibrium in the wind, and utilizes a Sobolev treatment of bound–bound transitions.

The code presented by Long & Knigge (2002) adopted a two-level approximation in the treatment of line scattering and used approximate excitation and ionization formulae for the computation of level emissivities. These approximations made the code efficient and thus able to handle a large set of atomic data for many chemical elements. However, the two-level approximation also meant that it was not suitable for modelling lines formed by non-resonance scattering or recombination.

Because the IR \( \text{H}^\prime \) lines form primarily by recombination, the code has been substantially modified to incorporate recently developed MC radiative transfer techniques which allow the formation of such lines to be modelled. In particular, ‘macro atoms’, as devised and tested by Lucy (2002, 2003), are used. This approach allows the radiative equilibrium constraint to be rigorously enforced at all times without approximation in the treatment of interactions between radiation and matter.

Initially, several MC simulations are performed to compute the temperature and degrees of excitation and ionization throughout the wind. For these ‘ionization cycles’ the MC quanta are launched with frequencies spanning a wide enough range to simulate all the important radiative energy inputs to the system. During each of these MC simulations, estimators for the radiative heating rate (e.g. due to photoionization) are recorded in each grid cell. At the end of the simulation, these rates are balanced against cooling rates to determine the local electron temperature, which is then adopted in the next simulation. This process is repeated until essentially all grid cells pass a chosen convergence threshold in electron temperature.
For this work, the code has been modified to also record high-precision MC estimators for the individual radiative rates (photoionization and bound–bound excitation) following Lucy (2003). At the end of each ionization cycle, these are used, together with the various collision rates and radiative decay rates, to compute level populations and the ionization fraction in each grid cell. These populations are used in the next iteration, allowing for the approximate analytical formulae for ionization and excitation employed by Long & Knigge (2002). No convergence criterion is enforced for the level populations at present. Lucy (2002) has shown that, provided the populations of the lowest levels are estimated sensibly, the indivisible-energy-packet MC method produces highly accurate emissivities even if the populations for the emitting upper levels are relatively poorly known. This insensitivity motivates our use of the MC method because it substantially reduces our reliance on detailed calculation of excited level populations for an adequate NLTE investigation of recombination line formation. We note that our convergence criterion on the electron temperature implies a corresponding convergence in the energy flow between the radiation field and the thermal energy pool. Because this energy flow is a summation of all the radiative heating processes in the hydrogen model, its behaviour implies good convergence amongst all the processes which are energetically important.

After the ‘ionization cycles’, a set of additional MC simulations is performed to compute the spectrum (the ‘spectral cycles’). During these cycles, the MC quanta are created in only a fixed frequency interval while the thermal, ionization and excitation states of each grid cell are fixed to the values previously determined as described above. By tracking the quanta, we compute the spectrum as seen by observers at different inclination angles in the frequency range of interest.

In all the calculations described below, the model structure and radiation field properties are discretized on to a two-dimensional (r–z) grid consisting of 3000 cells. During each MC calculation, the input radiative energy (which arises from the star and accretion disc) is divided into $3 \times 10^5$ indivisible quanta.

We have explicitly verified that our approach is adequate for the calculation of the spectrum by comparing results for models with identical input parameters using smaller and larger numbers of grid cells. These calculations differed by at most a few per cent in the computed H I line strengths from the standard (3000 cell) case. This implies that the number of packets, number of grid cells and the quality of the MC estimators are all sufficient for calculations to this degree of accuracy.

4 RESULTS

4.1 Observational constraints

Early observations of IR H I emission lines in massive YSOs (e.g. Simon et al. 1981) had insufficient signal-to-noise ratio to provide detailed information on the line shapes. Thus, subsequent theoretical work (e.g. Höflich & Wehrse 1987) was concerned primarily with modelling the observed line fluxes and flux ratios.

More recently, higher-quality data (e.g. Drew et al. 1993; Bunn et al. 1995) have allowed the line shapes to be studied in greater detail in several massive YSOs. In common with earlier work (e.g. Simon et al. 1981, 1983; Drew et al. 1993), Bunn et al. (1995) observed a moderately strong, pure-emission line of Br$\gamma$ in all of their targets. In most cases, they also reported weaker emission in Br$\alpha$ and Pf$\gamma$. Their observed line profiles are single-peaked and not shifted from the expected local rest velocity by more than a few $\text{km s}^{-1}$. Many of the profiles show line wings which extend to several hundred $\text{km s}^{-1}$ from the line centre, and in some cases these wings are clearly asymmetric. By considering wavelength-dependent line ratios (following Drew et al. 1993), Bunn et al. (1995) found evidence, in at least some cases, of hybrid profiles consisting of a narrow line core (which may have a nebular origin) and broad wings in which the line ratio is consistent with formation in an accelerating outflow.

High-resolution observations of several massive YSOs have very recently been presented by Blum et al. (2004). Interestingly, in their sample, at least one object (NGC 3576) has double-peaked, narrow-line profiles. However, it is difficult to study the broad-line wings in the Blum et al. (2004) data because the spectral coverage is too narrow to establish the underlying continuum with certainty.

In the following subsections, results of our models will be compared primarily with the observations presented by Bunn et al. (1995) because their spectra provide good constraints on both line strengths and shapes for a significant sample of objects. Unfortunately, owing to the great difficulty in establishing the extinction along the line of sight to massive YSOs, interpreting line fluxes and flux ratios for lines at different wavelengths is very difficult. It is known from Br$\alpha$/Pf$\gamma$ flux ratios that the H I lines are not well described by either the LTE or the Baker Menzel case B recombination assumptions; thus, the Br$\alpha$/Pf$\gamma$ ratio cannot be trusted as an indicator of the reddening (Höflich & Wehrse 1987). Therefore, in our discussion, we prefer to focus on EWs, EW ratios (EWRs) and line shapes because these are not affected by reddening. For quantitative comparison, Table 2 gives a summary of the range of observed EW, FWHM and half-width at zero intensity (HWZI) from Bunn et al. (1995). The table also gives the observed range of EWRs for Br$\alpha$/Br$\gamma$ and Br$\alpha$/Pf$\gamma$.

Hereafter, these EWRs will be referred to as EWR[Br$\alpha$/Br$\gamma$] and EWR[Br$\alpha$/Pf$\gamma$], respectively.

### Table 2. The observed range of properties of massive YSO H I IR lines in the sample discussed by Bunn et al. (1995).

| Line  | –EW (Å) | FWHM (km s$^{-1}$) | HWZI (km s$^{-1}$) |
|-------|---------|-------------------|-------------------|
| Br$\alpha$ | 4.8–87 | 55–155 | 50–415 |
| Br$\gamma$ | 2.4–23 | 70–150 | 70–270 |
| Pf$\gamma$ | 2.3–12 | 110–150 | 40–260 |
| Br$\alpha$/Br$\gamma$ | 1.1–4.4 | | |
| Br$\alpha$/Pf$\gamma$ | | 3.0–7.2 | |

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The computed line profiles are complex, usually exhibiting double peaks, which become more pronounced at larger $\theta_{\text{obs}}$. This is in contrast to the observations where only single-peak profiles are usually observed (see Section 4.1). Also, the computed profiles are too broad (FWHM ranging from 300 to 600 km s\(^{-1}\)) as a function of $\theta_{\text{obs}}$). Part of this discrepancy between model and observations may be explained by contamination of the observed profiles by narrow nebular emission; there is some evidence for hybrid line profiles with narrow cores (see Section 4.1). However, the HWZI measurements also suggest that the observed line profiles do not extend more than 200–300 km s\(^{-1}\) from the line centre in most cases.

The large linewidths and double-peaked profiles arise due to the rotational velocities in the region of line formation. Fig. 6 identifies the region of line formation for the Br\(_\alpha\), Br\(_\gamma\) and Pf\(_\gamma\) lines in model A; specifically, the plots show the amount of energy that escapes the region of line formation for the Br\(_\alpha\) line. To obtain models which produce narrower lines, either more low-velocity gas must be added, or high-velocity gas must be removed. The simplest way in which to introduce low-velocity gas is by increasing the outer disc radius ($r_{\text{disc}}$); models with wider discs are presented in Section 4.3. To remove high-velocity gas requires a reduction in the wind density at small values of $r$. Given that the inner disc is brighter than the outer disc, it seems unlikely that a radiatively driven flow will not have greatest mass-loading at small radii. Therefore, the most plausible way in which to eliminate

![Figure 5](image-url)
Table 3. EWs and FWHM for the Brγ, Brγ and Pfγ lines at different viewing angles (θobs). The values of FWHM have an accuracy of around ~50 km s\(^{-1}\), limited by the frequency gridding of the calculations. The accuracy of the EWs is limited by MC noise in the spectrum. Typically, the MC noise in the continuum is <2 per cent.

| Model | θobs (°) | EW (Å) | FWHM (km s\(^{-1}\)) |
|-------|----------|--------|----------------------|
| Model A (reference model with reflecting disc) | | | |
| Brγ  | 30       | 44     | 300                  |
| Brγ  | 45       | 4.0    | 290                  |
| Pfγ  | 60       | 7.2    | 340                  |
| Model B (reference model with reprocessing disc) | | | |
| Brγ  | 3.1      | 430    | 4.2                  |
| Brγ  | 3.4      | 360    | 4.8                  |
| Pfγ  | 3.4      | 360    | 4.8                  |
| Model C (as Model B but with mass loss rate enhancement) | | | |
| Brγ  | 7.2      | 27     | 300                  |
| Brγ  | 3.4      | 340    | 4.5                  |
| Pfγ  | 3.4      | 340    | 4.5                  |
| Model D (as Model A but with disc out to 100 \(r_\ast\)) | | | |
| Brγ  | 4.6      | 24     | 300                  |
| Brγ  | 3.4      | 360    | 4.5                  |
| Pfγ  | 3.4      | 360    | 4.5                  |
| Model E (as Model C but with disc out to 100 \(r_\ast\)) | | | |
| Brγ  | 6.6      | 4.5    | 340                  |
| Brγ  | 4.5      | 340    | 4.5                  |
| Pfγ  | 4.5      | 340    | 4.5                  |
| Model F (disc with inner hole, see Section 4.4) | | | |
| Brγ  | 2.8      | 2.2    | 260                  |
| Brγ  | 2.8      | 220    | 3.8                  |
| Pfγ  | 2.8      | 220    | 3.8                  |

Note. aFor model B, the Brγ and Pfγ lines are very weak and only appear marginally above the MC noise; therefore, the entries for these lines give only upper limits on their EW.

high-velocity gas is not to change the prescription of mass-loading but rather to consider models in which either the stellar radius is larger than that adopted in the reference model or the disc inner radius is several times greater than the adopted stellar radius. An example of the latter, a model with an empty inner cavity in the disc, is discussed in Section 4.5.

To assess the relative importance of the disc wind and stellar wind component, results from a calculation considering only the disc wind component were compared with those which include the stellar wind. These two calculations give virtually identical results; this is not unexpected because it is already known that a spherical wind would require a mass-loss rate at least an order of magnitude greater than that adopted in the reference model or the disc inner radius. An example of the latter, a model with an empty inner cavity in the disc, is discussed in Section 4.5.

To increase the line EWs in the presence of a reprocessing disc the wind density (and hence emission measure) needs to be increased. Therefore, a further model (model C) has been constructed – it is identical to model B saving that the disc wind mass-loss rate has been increased by a factor of 4. A higher mass-loss rate may be feasible even under the assumption of driving purely by radiation because the absolute mass-loss rates provided by the hydrodynamical model of Drew et al. (1998) may be uncertain by a factor of a few owing to the parametrisation of the line-driving force. EWs and FWHM for model C are given in Table 3 and the line profiles computed from this model are shown in Fig. 7.

The simple treatment of reprocessing adopted (see Section 2.2.2) means that the disc is much brighter at IR wavelengths in model B than model A. Thus, although the wind parameters in model B are unchanged, the EWs of all the emission lines are much smaller (the EWs are given in Table 3). At moderate to high θobs, the model B EWs for Brγ and Pfγ are comparable to the observed EWs in the weaker sources reported by Bunn et al. (1995). However, the computed Brγ line is very weak.

4.3 Reprocessing of radiation by the disc (models B and C)

In model A (discussed above) it was assumed that the photons striking the accretion disc were reflected rather than absorbed. To investigate an alternative simple hypothesis, namely that the disc absorbs and thermally re-emits the radiation which strikes it (see Section 2.2.2), a second model (model B) is now considered. This is the extreme, optically thick disc case. All the system parameters (Table 1) for model B are identical to those of model A, saving that the stellar wind component is omitted (see above).
4.4 Influence of the outer radius of the disc

The outer disc radius parallelling that of Drew et al. (1998) and adopted in models A–C is, arguably, rather small. In principle, line formation in a wind rising from the outer parts of a larger disc could eliminate the double-peaked line shape obtained with models A–C by adding low-velocity gas. In this section, two more models (models D and E) are considered: these models are identical, respectively, to models A and C saving that the outer disc radius is set to 100 $r_*$, rather than 10 $r_*$.

The computed line profiles for model D are shows in Fig. 8 and the EWs for models D and E are given in Table 3. The differences between the profile shapes shown in Figs 5 and 8 are generally fairly small. The double-peaked shape is slightly filled in when the larger disc is considered. However, the assumption that the mass-loading of streamlines is proportional to the luminous flux (see Section 2.2.3) means that the majority of the mass loss still originates from the inner disc where velocities are high. The most important consequence of the larger disc is the increase in the IR continuum level (see Fig. 3 and the discussion in Section 2.3.2). The brighter continuum means that, when the disc is bigger, the line EWs are all smaller. Also, the EWR[$\text{Br}\alpha$/Pf$\gamma$] is smaller – the larger disc radius increases the continuum around 4 $\mu$m by more than at 2 $\mu$m (see Fig. 3).

For model D, the Br$\alpha$ EWs lie comfortably in the mid-range of the observed values and the EWR[$\text{Br}\alpha$/Pf$\gamma$] is similar to that found in model A. The EWR[$\text{Br}\alpha$/Pf$\gamma$] is smaller in model D than A (as required) but the improvement is less significant than obtained with model C (see Section 4.2). Model E predicts smaller EWs, but still within the range observed. The EWR[$\text{Br}\alpha$/Pf$\gamma$] in model E is closer to that observed than in any of the other models – this follows because model E benefits from the improvement in this ratio resulting from both a higher line opacity (density) and stronger disc continuum.

4.5 Influence of a central hole in the disc

It is apparent that a failing of models A–E in comparison with the data is that the computed line profiles are too broad. One of two possible solutions to this problem is to invoke an inner hole in the accretion disc, thereby removing the highest velocity material from the region of line formation. Optically thin inner cavities in accretion

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Table 4. Computed Br$\alpha$ line fluxes and flux ratios Br$\alpha$/Br$\gamma$ and Br$\alpha$/Pf$\gamma$ at different viewing angles. Fluxes are given in units $10^{-13}$ erg cm$^{-2}$ s$^{-1}$ for an unreddened source at a distance of 1 kpc.

| Model | $\theta_{\text{obs}}$ | Br$\alpha$ flux | Br$\alpha$/Br$\gamma$ | Br$\alpha$/Pf$\gamma$ | Br$\alpha$/Pf$\gamma$ |
|-------|----------------|----------------|-----------------|-----------------|-----------------|
| A (reference model with reflecting disc) | $30^\circ$ | 5.1 | 1.72 | 4.86 |
|      | $45^\circ$ | 5.3 | 1.70 | 4.74 |
|      | $60^\circ$ | 4.9 | 1.66 | 4.67 |
|      | $70^\circ$ | 4.3 | 1.59 | 4.48 |
|      | $80^\circ$ | 3.3 | 1.48 | 4.13 |
|      | $85^\circ$ | 2.6 | 1.36 | 3.81 |
| B (reference model with reprocessing disc) | $30^\circ$ | 4.8 | 1.99 | 3.07 |
|      | $45^\circ$ | 5.0 | 1.37 | 4.09 |
|      | $60^\circ$ | 4.5 | 1.73 | 3.34 |
|      | $70^\circ$ | 3.9 | 1.72 | 3.84 |
|      | $80^\circ$ | 3.1 | 1.85 | 3.65 |
|      | $85^\circ$ | 2.6 | 1.72 | 3.77 |
| C (as Model B but with mass-loss rate enhancement) | $30^\circ$ | 43 | 0.91 | 3.05 |
|      | $45^\circ$ | 47 | 0.93 | 3.01 |
|      | $60^\circ$ | 43 | 0.93 | 3.16 |
|      | $70^\circ$ | 37 | 0.95 | 3.27 |
|      | $80^\circ$ | 27 | 1.05 | 3.69 |
|      | $85^\circ$ | 20 | 1.19 | 4.09 |
| D (as Model A but with disc out to 100 $r_*$) | $30^\circ$ | 4.0 | 1.54 | 4.50 |
|      | $45^\circ$ | 4.1 | 1.59 | 4.61 |
|      | $60^\circ$ | 4.0 | 1.60 | 4.66 |
|      | $70^\circ$ | 3.6 | 1.59 | 4.49 |
|      | $80^\circ$ | 3.0 | 1.56 | 4.33 |
|      | $85^\circ$ | 2.5 | 1.52 | 4.18 |
| E (as Model C but with disc out to 100 $r_*$) | $30^\circ$ | 25 | 1.32 | 3.07 |
|      | $45^\circ$ | 26 | 1.40 | 3.44 |
|      | $60^\circ$ | 25 | 1.49 | 3.66 |
|      | $70^\circ$ | 23 | 1.51 | 4.11 |
|      | $80^\circ$ | 19 | 1.56 | 4.57 |
|      | $85^\circ$ | 16 | 1.64 | 4.90 |
| F (disc with inner hole, see Section 4.4) | $30^\circ$ | 19 | 2.37 | 6.94 |
|      | $45^\circ$ | 19 | 2.37 | 6.20 |
|      | $60^\circ$ | 19 | 2.29 | 5.82 |
|      | $70^\circ$ | 17 | 2.18 | 5.60 |
|      | $80^\circ$ | 16 | 2.06 | 5.17 |
|      | $85^\circ$ | 14 | 2.03 | 4.93 |

Note. *For model B, the Br$\gamma$ and Pf$\gamma$ lines are very weak and only appear marginally above the MC noise; therefore, the entries for these lines give only lower limits on the appropriate flux ratios.
moving them will push the SED of the disc to the red. This will increase the continuum level at Brα relative to Brγ and therefore reduce the EWR[Brα/Brγ] as required. However, a quantitative investigation of this possibility goes beyond the scope of this paper because more sophisticated models for the disc emission than used here would be required.

Consideration of models in which the disc has a central hole represents a significant departure from the Drew et al. (1998) model and therefore, until further hydrodynamical calculations are performed, it is difficult to place useful constraints on the likely geometry and parameters for mass loss from such a disc. Nevertheless, for illustrative purposes, a model adopting the same wind opening angles (θmin, θmax) and mass-loss rate as the reference model (model A; Section 4.1) but with an inner disc radius of rmin = 5 rs and outer disc radius of rdisc = 100 rs has been constructed (model F) – this corresponds to a disc with a circular inner hole of ~0.1 au. It is noted that, conceptually, invoking a wind launched significantly further out than the stellar surface is reminiscent of the photoevaporation model (e.g. Hollenbach et al. 1994). However, the distance from the central star at which the mass loss occurs here is still much smaller than expected from photoevaporation. It is, however, comparable to the smallest disc radii inferred from CO observations by Bik & Thi (2004).

The computed FWHM and EWs for model F are tabulated in Table 3 and the profiles are shown in Fig. 9. The EWs are smaller than those for model A because the density in the wind is lower, a result of the radial dependence of the volume element in a cylindrical polar system. The lower density also leads to lower opacity and hence larger ratios of Brα to Brγ and Pfγ. However, as anticipated, the model F lines are narrower than in model A, by up to 100 km s−1 in FWHM for moderate inclination angles. The profile widths at the base are also smaller; in model F the profiles cut off at ~300 km s−1 from the line centre. Thus, holes of the size considered here, or a little larger, could explain why the HWZI measurements of Bunn et al. (1995) are rather smaller than would be expected based on models A–E.

Given that there are no strong constraints on the hole size, geometry or mass-loss rate appropriate for the model here it is not possible to draw definitive conclusions. However, it seems that models with an inner disc cavity have the potential to resolve the discrepancies between the computed disc wind line profiles and the observations. Model F also suggests that the second possibility mentioned in Section 4.2 – that of an enlarged stellar radius – can also provide a possible solution because increasing the stellar radius will affect the linewidths in a similar way to introducing an inner gap in the disc. Constraints on the size of any inner hole, the stellar radius and the geometry of the disc wind are needed in order to proceed. These could be provided via sophisticated observational techniques such as interferometry (which has already been applied to Herbig Ae/Be stars by, for example, Monnier et al. 2005) or spectropolarimetry (as discussed by Vink, Harries & Drew 2005).

5 DISCUSSION

As mentioned in Section 4, direct confrontation of theoretical line fluxes with observations is difficult owing to the uncertainty in the extinction along lines of sight to massive YSOs. However, on comparing EWs – the quantities most readily extracted from observations – the radiative transfer calculations presented above lead us to conclude that model disc winds, such as that obtained by Drew et al. (1998), do predict Hα line strengths consistent with observations of massive YSOs. This matching is achieved for total mass-loss rates between 0.3 and 1.2 × 10−7 M⊙ yr−1, in contrast with previously...
calculated spherical models for early B stars which require mass-loss rates up to $10^{-6}$ $M_\odot$ yr$^{-1}$ (Simon et al. 1983; Nisini et al. 1995).

There are, however, some difficulties when the models are considered in detail. Although the computed EWR[$\text{Br}\alpha/\text{Pf}\gamma$] agrees well with observations, the EWR[$\text{Br}\alpha/\text{Br}\gamma$] tends to be overpredicted by the models. We have investigated the effect of a higher density on this ratio by considering models with greater mass-loss rate, e.g. model C. (Recall that the model density is sensitive to several parameters in addition to the mass-loss rate and thus there is a degree of degeneracy among these quantities; see Section 2.3.5.) As expected, increasing the wind density decreases the EWR[$\text{Br}\alpha/\text{Br}\gamma$] owing to the greater optical depth. However, to fully explain the EWR discrepancy solely by such a modification is difficult because the absolute values of the EWs grow rapidly if the density is raised. At the same time, this EWR is very sensitive to the assumed
underlying SED, owing to the significant wavelength difference between the Br$\alpha$ and Br$\gamma$ lines (unlike Br$\alpha$ and Pf$\gamma$ which lie at similar wavelengths). Observationally it is clear that there is genuine diversity in the IR SEDs of massive YSOs (e.g. Henning et al. 1990). In our models we have considered only two limiting cases for the treatment of the SED and have not concerned ourselves with trying to fit specific objects. To determine whether the EWR[Br$\alpha$/Br$\gamma$] discrepancy is unavoidable, there is now a need to move on to fitting observations of individual well-observed sources with reliable reddening estimates.

Important differences are also evident in comparisons of the line profiles obtained from our models and those typically observed in massive YSOs. To illustrate this, Fig. 10 compares the observed Br$\alpha$ profile for GL989 (taken from Bunn et al. 1995) with computed profiles from two of the models. GL989 is chosen here because the line profiles for this object have strong extended wings and, in contrast to several of the other objects in the Bunn et al. (1995) sample (e.g. S106IR), have simple profiles suggesting a single dominant region of line formation. The comparison models and viewing angles (model B with $\theta_{\text{obs}} = 60^\circ$ and model E with $\theta_{\text{obs}} = 45^\circ$) were selected because they predict Br$\alpha$ EWs close to the observed value, thereby allowing a direct comparison of profile shape.

The figure shows that the model B Br$\alpha$ profile at $\theta_{\text{obs}} = 60^\circ$ is too broad and, in contrast to the observations, is double-peaked. The model E profile ($\theta_{\text{obs}} = 45^\circ$) is in better agreement with the observation – the combination of higher optical depth in the model (owing to the increased mass-loss rate) and lower viewing angle reduce the profile width and suppress the double peaks – but a significant discrepancy remains. To resolve this difference in line shape between the models and typical observations, one could invoke even smaller inclination angles. Although viewing angles are not known for most luminous YSOs, this is not an attractive solution because
small viewing angles (close to pole-on) are statistically disfavoured in an unbiased sample. Furthermore, at least one of the objects discussed by Bunn et al. (1995) is known to be viewed almost edge-on (S106IR; Solf & Carsenty 1982). Thus, we prefer to pursue resolutions to the two styles of line shape discrepancies which do not rely on orientation effects.

Increasing the physical extent of the disc from which the wind is launched does not readily eliminate the double-peaked line shape from our models (models D and E). Although some of the wind does occupy regions with lower rotational velocities when the disc is made larger, our assumption that the mass-loading is proportional to the luminous flux of the disc means that most of the mass in the wind is still launched at small radii. The problem of reconciling observed single-peaked line profiles with theoretical predictions of double peaks has arisen elsewhere, particularly in studies of nova-like variables (see, for example, Horne 1997) and active galactic nuclei (AGN). In the context of AGN, Murray & Chiang (1997) have argued that substantial radial velocity shear in a disc wind can suppress the formation of double-peaked profiles as required. For this to occur, it is necessary that line optical depths are high such that photon escape is strongly favoured in the poloidal direction where accelerating outflow ensures steep velocity gradients. It is this difference between model C, with enhanced mass loss, and model A that explains the relatively flat-topped profiles in Fig. 7, compared to Fig. 5. Hence there is scope to reorganize model parameters in order to exploit this mechanism to suppress double peaks. In particular, a way of raising line opacity without also raising Brγ EWs is needed. This will warrant further investigation in future work, focusing on fitting observations of specific objects.

Some of the discrepancies, in particular the large linewidths predicted by the models, may be explained by departures from the particular disc wind geometry adopted (which was motivated by the Drew et al. 1998 model). Two interesting possibilities are those of an enlarged radius for the central star, relative to a main-sequence radius, or of an inner gap in the YSO disc. These possibilities have rather similar consequences: by moving the disc wind out to larger radial distances from the central object, the correspondingly lower rotation velocities reduce the extent of the line wings and make the double peaks less prominent (this is illustrated by our model with a cavity in the inner disc, model F). Also, theSED for a disc with a hole will be redder than that for a complete disc, helping to explain the EW[Brγ/Brγ] discrepancy. These alternatives might be distinguished by observational techniques that probe the inner disc geometry (e.g. interferometry and spectropolarimetry) while the influence of a gap on the SED needs to be investigated fully in subsequent work incorporating more sophisticated treatments of the disc SED than used here.

A third possibility is that of disc winds in which the streamlines diverge less at large distances. In our models, the divergence of the streamlines is imposed by our adopted ‘split dipole’ geometry. In a geometry with less divergence of the flow, the density would be higher in the outer parts of the wind for a given mass-loss rate and velocity law. The increased emission measure at large radii would help to wash out the double-peaked profiles which form when the emission is dominated by gas in rotation close to the central object. For appropriate viewing angles, line-of-sight optical depths would also be larger for a less divergent outflow. As has already been noted, higher optical depths present a promising solution to part of the EW[Brγ/Brγ] discrepancy. Thus, in the context of studying particular objects in detail, considering a range of different disc wind geometries is likely to prove fruitful in future work.

These issues aside, the major success of our radiative transfer simulations is their support of the hypothesis that disc winds can play a significant role in creating the Hı lines of massive YSOs. In particular, the departure from one-dimensional wind models has alleviated the need to invoke the uncomfortably large mass-loss rates required in earlier spherical models. Further investigations of the applicability of the disc wind model to particular objects are now warranted.

ACKNOWLEDGMENTS

SAS thanks L. Lucy for several useful discussions relating to this work and L. Mendes for technical support in use of the Imperial College Astrophysics Beowulf cluster.

This work was undertaken while SAS was a UK Particle Physics and Astronomy Research Council supported postdoctoral research assistant at Imperial College London (PPA/G/S/2000/00032).

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