Accretion Phenomena and Related Outflows, IAU Colloquium 163
ASP Conference Series, Vol. 121, 1997
D.T. Wickramasinghe, L. Ferrario, and G.V. Bicknell, eds.

A Two Dimensional Photoionization Front Model for YSO Envelopes in the Orion Nebula

Ralph S. Sutherland

The Australian National University Astrophysical Theory Centre, Mount Stromlo and Siding Spring Observatories, and the School of Mathematical Sciences, Canberra, ACT 0200, Australia

Abstract. A simplified axi-symmetric 2.5D radiative transfer model of a YSO envelope (HST-1, 177-341, O'Dell & Wen 1994) in the Orion Nebula (NGC1976) is computed assuming only a spherical distribution of gas with a powerlaw density function. The model fits recent Hubble Space Telescope data (Bally *et al.* 1996) very well on 10^{15} cm scales, suggesting that the morphology of the *'proplyd'* objects is due to photoionization on this scale rather than a direct wind-wind interaction (Henney *et al.* 1996). The fact that a simple spherical distribution of gas fits the ionization observations so well also implies that somewhere between the scale of the YSO accretion disk and the observed ionization front radius the gas distribution has changed.

1. Introduction

Recent HST observations (O'Dell, Wen & Hu 1993; O'Dell & Wen 1994; Bally, Devine & Sutherland 1995) have detected compact knots of emission in the Orion Nebula. These knots show a characteristic *'teardrop'* or *'cometary'* morphology, with all the tails pointing away from the brightest of the Trapezium cluster stars, θ^1C Ori. Some of these objects corresond to the Laques & Vidal objects (Laques & Vidal 1979) or with the *PIG* objects detected in the radio by Churchwell *et al.* (1987). Some objects contain low-mass stars detectable in the optical HST observations, and McCaughrean & Stauffer (1994) have shown that indeed virtually all these compact knots contain a central star, in infrared observations. In addition, the densities seen in the Churchwell *et al.* observations of 10^6 cm^{-3} or more, would imply that the central stars would be obscured if all the gas were in a spherical distibution right down to the star. This is taken as evidence of disk like distributions of gas, which is further supported by IR spectral observations. Henney *et al.* (1996) have argued that this means that these objects are due to a disk wind - stellar wind interaction and have proposed that the orientation of the disks gives rise to slight non-axisymmetic geometry seen in some objects. Here a spherical ionization front model is chosen, however it does not make any assumption about the density profile inside the ionization front, which must become non-spherical at some interior point for the stars to be seen.

The atomic physics and emission modelling in the Henny *et al.* work was, necessarily, highly simplified, and the photionization hypothesis was not tested at all. Here a more detailed atomic/dust physics model is used to test the photionization possibility.

2. Modelling

A single model is presented. It is not intended as a final model, rather it is a feasibilty test of the spherical photoionization hypothesis. A spherical gas distribution was constructed with a radial density profile, $\rho \propto r^{\alpha}$, $\alpha = -2$. This a simple model with a spherical constant dM/dt. Other profiles are of course possible and are being investigated currently.

2.1. Equilibrium Photoionization

Equilibrium photionization modelling and spectrum synthesis is carried out using MAPPINGS II (Sutherland 1993). The model includes up to 16 elements, using multi-level ions, detailed contintuum and recombination calculations, and dust grains. No molecules are modeled. A spherical distribution is sampled at a series of impact parameters, with separations such that, locally, the *'on-the-spot'* approximation would hold, so that to a first approximation each impact parameter integation is independent of the others. The *'on-the-spot'* approximation is not used, rather a locally plane-parallel integration with a diffuse field is used along each line. Each impact parameter model consists of approximately 200 sub-zones and terminates at 1% ionization levels where molecular physics would be expected to take over.

The radiation field used here corresponds to a Kurucz (1992) LTE atmophere for 40,000 K, $\log(g) = 4.5$ and Solar abundances. This field was scaled to match the known luminosity of θ^1C Ori, and then diluted to corresphond to the observed separation of the target object (HST-1, 177-341) ($\approx 10^{17}$ cm) from the radiation source. No absorption in the intervening space between θ^1C Ori and HST-1 is considered here. No diffuse field from the ambient nebula is included.

Since the luminosity of θ^1C Ori and the separation between the ionization-front and the star are known, the observed ionization parameter as determined by the observed [OIII]/Hα ratio, implies a density in the ionized region of $\approx 10^5$ cm^{-3}. The powerlaw was chosen to give this density at $r = 10^{15}$cm.

2.2. Dust

Gas abundances were taken as solar (Anders & Grevesse 1989) and a dust/gas mass ratio of 0.9% was used (consistent with general ISM values). This dust was formed consistently from the initial composition gas using depletion values suggested by Shull (1993), so that $z_{\rm tot.} = z_{\rm gas} + z_{\rm dust}$ = Solar values.

The dust properties in this model are conservative. They correspond to a minimum of photo-electric heating and minimum additional absorption/scattering of the radiation by dust. The dust properties are based purely on a large refractory (astronomical silicate and Graphite mixture) population of grains with an MRN ($dN/da = a^{-7/2}$) size distribution(Mathis, Rumpl & Nordsiek 1977). The absorption and scattering cross-sections are modeled as a function of energy

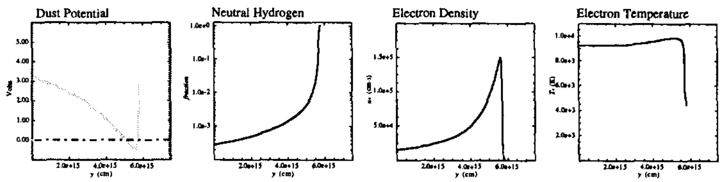

Figure 1. Center line model structures.

(Laor & Draine 1993). The mixture was set to satisfy $E(B-V)/A_V \approx 3.1$ inline with general ISM values. Very small grains and PAH molecules are not included in this model, but will be included in future work.

The properties of dust in Orion may not be well modelled by these parameters. However, as dust physics is generally poorly understood in a quantitative way a standard dust model is used for the purpose of providing a baseline for comparisions with other models. It can be expected that as small grains and organic compounds are added to the dust mixture, the effects of dust heating and absortpion will increase. In the model here dust scattering is treated in a simple way, the mean scattering angle as a function of frequency is used to distribute a fraction of the direct radiation into the local diffuse field at a given point in the model, and the diffuse field is integrated in an outward fashion.

The photo–electric current, J_ν, due to the UV field, $\Phi(\nu)$, is computed here by: $J_\nu = A_g \int_B^{14eV} \left[\int_{Max(0,U)}^{14eV-B} f(\epsilon,\nu)d\epsilon\right] Q_{\rm abs}(\nu)Y(\nu)\Phi(\nu)d\nu$, where U is the grain potential and A_g is the grain area. This current is balanced by collisional currents due to electrons and protons (Draine & Sutton 1987) to give a grain potential which is in turn used to iteratively solve this equation. The Yield function $Y(\nu)$ is modelled with a form $Y(\nu) = Y_\infty(1 - h\nu/B)$ as in Drain (1978), however here $\Phi(\nu)$ is a detailed function of the initial spectrum for the star and the result of radiatve transfer through the model. Consequently the grain charge is solved numerically at each point.

Radiation pressure on the dust grains is computed, but not applied, at each point in this equilibrium static model. The acceleration due to radiation pressure is estimated by $dv/dt = (LQa^2)/(4cr_*m) - v/t_s$, with $t_s = 0.17a\rho[n(kTm)^{1/2}ln\Lambda]^{-1}$ for charged grains and $t_s = 0.70a\rho[(n(kTm)^{1/2}]^{-1}$ for neutral grains (*c.f.* Spitzer 1978 for details). Here, a detailed calculation of Λ, the Coulomb integral, absorption, $Q(\nu)$, and radiation field L is used. The distance of the grain from the star is r_*. The resulting drift velocities in the current model are well approximated by: $v_{\rm drift} = -8.5{\rm cm/s}\,[\frac{n_e}{10^5}]^{-1}[\frac{r}{10^{17}}]^{-2}[\frac{L}{10^5}][\frac{Q}{1.0}]$, for charged grains, and $v_{\rm drift} = -2.54 \times 10^5{\rm cm/s}\,[\frac{n_e}{10^5}]^{-1}[\frac{r}{10^{17}}]^{-2}[\frac{L}{10^5}][\frac{Q}{1.0}]$ for neutral grains. So, the dust drift velocities against the outflow could become comparable to the gas flow velocity ($\approx 10^6$ cm/s) for neutral grains if the grain lies close enough to θ^1C Ori. Other grain types, such as small organic grains, could become neutral at different radii due to their differing work functions and photo–electric currents.

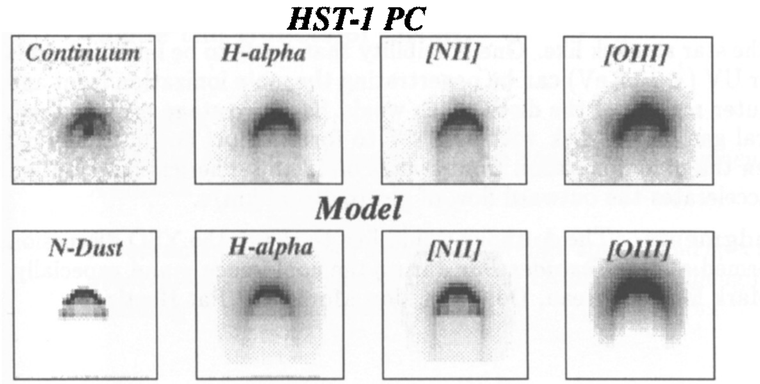

Figure 2. Comparison of 3D models with HST narrow band PC observations.

3. Results

Neglecting the details of the tail formation, which is a hydro–dynamical problem, we consider only the front hemisphere of the model, on the side facing towards the radiation source. Figure 1. shows a one dimensional slice along the line from the star towards the centre of the model. Plotted are the dust grain potential, the ionization fraction of hydrogen, and the electron density & temperature. Note the dust can become neutral or negatively charged near the ionization front.

In figure 2, multi-band PC images from the HST of the head region of HST-1 are shown. Comparison with the synthetic model images, formed by rotating the 2D models and projecting the 3D structure, are shown. The volume where the dust can become neutral is also shown and this shows a good corresondance with the continuum image. This may be due to the buildup of dust as it is retarded in the outflow by the radiation pressure of the incoming radiation. The overall agreement is quite good. The observations show a greater lateral ionization of [OIII] than the models, which may be due to additional diffuse radiation from the ambient nebula.

4. Conclusions

It is possible to match the observations of the heads of the *'proplyd'* structures in the Orion nebula using an ionization front in a spherical distribution of gas at radii of $\approx 10^{15}$ cm. The continuum images may be influenced by the build up of dust by back–pressure of radiation, but this is not conclusive. The predicted line ratios and spatial ionization structure are consistent with a spherical distribution so wind–wind bowshock structures, if they exist, must lie at a larger radius. The [OIII] arcs seen in Bally, Devine & Sutherland (1995) at a radius of $\approx 10^{16}$ cm may be the wind bowshocks.

This result raises the question of why the gas is spherical, if the inner regions near the star are disk like. One possibility that needs to be investigated is whether softer UV (< 13.6 eV) can be penertrating the main ionization front and heating the outer regions of the disks. This would be a two stage process then, heating neutral gas off the disk with soft UV to form a slow flowing spherical cloud and then the main ionization front stands off in the spherical distribution and further accelerates the outward flow of gas to 10s of km/s.

Acknowledgments. The Authour would like to thank the YSO discussion group that formed at the *Cascades Bar* during the conference – and especially, John Bally, Mark McCaughrean, Doug Lin, Jon Morse and Pat Hartigan.

References

Anders E. & Grevesse N. 1989, *Geochim. Cosmochim. Acta*,53,197

Bally, J., Sutherland, R. S., and Devine D., 1996, AJ, in prep

Bally, J., Devine, D. and Sutherland, R. S., 1995, RevMexAA (Serie de Conferencias), 1, 19

Churchwell, E. B., Felli, M., Wood, D. O. S. & Massi, M. 1987, ApJ, 321,516

Draine B. T. 1978,ApJS, 36, 595

Draine B. T. & Sutton B., 1987,ApJ, 320, 803

Henny, W. J., Raga, A. C., Lizano, A., and Curiel, S. 1996, ApJ, 000, 000

Laor, A., & Draine B. T., 1993,ApJ, 402, 441

Laqes, P. & Vidal, J. L. 1979,å, 73, 79

Mathis, Rumpl, Nordsiek 1977, ApJ,217,425

Kurucz, R. 1992, *private communication*

O'dell, C. R., Wen, Z. and Hu, X., 1993, ApJ, 410, 696

O'dell, C. R. and Wen, Z., 1994, ApJ, 436, 194

Shull M. J., 1993, *Physica Scripta*,T47,165

Sutherland R. S., 1993, *PhD Thesis*,Mount Stromlo & Siding Spring Observatories, ANU

Spitzer L., 1978, *Physical Processes in the Interstellar medium*,(NewYork:Wiley-Interscience)

Discussion

J. Steinacker: Does your code include scattering of the radiation by the dust particle (2D self consistently)?

R. Sutherland: Yes.