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HYDRODYNAMIC SIMULATIONS OF PROPLYD BOWSHOCKS

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RESUMEN

En la nebulosa de Orión se han encontrado arcos de emisión débil asociados con los *proplyds*. Estos arcos se localizan a 0.5–4 segundos de arco de los *proplyds*, en dirección de la estrella ionizante (θ^1 C Ori) y son comunmente interpretados como choques de proa, resultado de la colisión entre el flujo fotoevaporado del *proplyd* y el viento estelar altamente supersónico (1000 km s^{-1}) de θ^1 C Ori. Nosotros presentamos simulaciones hidrodinámicas bidimensionales de la interacción entre los dos vientos. Comparamos los resultados de nuestra simulación con la solución analítica que da la posición y forma de la cáscara delgada formada por la interacción de dos vientos (esférico y planoparalelo). Hacemos la comparación entre el mapa de intensidad predicho de nuestras simulaciones y las observaciones del *proplyd* 167–317.

ABSTRACT

Faint high–ionization arcs of emission are found to be associated with some of the proplyds in the Orion nebula. These arcs are typically offset by 0.5–4 arcsec from the proplyds, in the direction of the ionizing star (θ^1 C Ori) and have commonly been interpreted as bowshocks, resulting from the collision between the transonic photoevaporating flow from the proplyd and the highly supersonic (1000 km s^{-1}) stellar wind from θ^1 C Ori. We present two–dimensional hydrodynamic simulations of the wind–wind interaction (photoevaporating flow and supersonic wind). The results of our numerical simulation with the analytical solution for the position and the shape of the thin shell formed are compared by the interaction between two winds (spherical and plane-parallel). We compare the predicted intensity maps of our simulations with observations of the proplyd 167–317.

Key Words: **HYDRODYNAMICS — ISM: INDIVIDUAL (ORION NEBULA) — ISM: JETS AND OUTFLOWS**

1. INTRODUCTION

The proplyds are bright compact emission line knots (Laques & Vidal 1979; Garay, Moran & Reid 1987; O'Dell, Wen & Hu 1993; O'Dell & Wong 1996; O'Dell 1998; Bally et al.1̃998) surrounding young low–mass stars (Meaburn 1988; McCaughrean & Stauffer 1994), first discovered in the inner region of the Orion nebula (M42). They have been interpreted in terms of photoevaporation flows from circumstellar disks (Henney et al.1̃996; Johnstone, Hollenbach & Bally 1998; Henney & Arthur 1998; Störzer & Hollenbach 1999; Henney & O'Dell 1999; Richling & Yorke 1998; 2000), induced by the UV radiation from the principal exciting star of the nebula, θ^1 C Ori (O7V). Many of these objects show a cometary (head–tail) morphology, in which the tail points away from the star θ^1 C Ori. The proplyds that lie closest to θ^1 C Ori are accompanied by concentric arcs of bright [O III] and Hα emission, at distances of 0.5–4 arcsec from the ionization front (IF). These arcs are also visible in 10μm emission from silicate dust (Hayward, Houck & Miles 1994) and are interpreted as bowshocks created by the interaction between stellar wind of θ^1 C Ori and the photoevaporating flow from the proplyd (Bally et al.1998). Proper motion measurements (Bally, O'Dell & McCaughrean 2000) and spectroscopy (Henney 2000) indicate that the shocks are stationary structures, as is expected on the above interpretation.

Preliminary results from numerical hydrodynamic simulations of these bowshocks were presented in García-Arredondo, Arthur & Henney (2000), in which it was shown that the radii of the shocks associated with the proplyds closest to θ^1 C Ori were consistent with an interaction with the free–flowing supersonic stellar wind from the O star. In the present paper, we present a more detailed comparison between the numerical models and a particular proplyd, M42 167–317.

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2. THE NUMERICAL SIMULATION AND COMPARISON WITH THE ANALYTICAL MODEL

To explain the bowshocks, we present two–dimensional hydrodynamic simulations of the wind–wind interaction using a second-order, Eulerian, Van Leer Flux Splitting scheme. The equation of state for the stellar wind gas is taken to be adiabatic ($\gamma = 5/3$) since its density is so low that the cooling time greatly exceeds the dynamic time of the flow. The proplyd transonic flow, on the other hand, is assumed to be quasi–isothermal ($\gamma = 1.01$), which is justified since the photoelectric heating and radiative cooling rates for this component exceed the cooling rate due to expansion. The adiabatic index, γ, is advected as a passive scalar.

The proplyd parameters used are those derived from observations of the proplyd 167–317 (Henney, García-Díaz & Kurtz 2001): i.e., density of particles at the IF, $n_{\rm if} = 2.5 \times 10^6$ cm^{-3}, radius of IF, $R_{\rm if} = 8.0 \times 10^{14}$ cm, distance between the proplyd and star θ^1 C Ori, $D = 5.05 \times 10^{16}$ cm. For the star θ^1 C Ori we adopt a stellar mass–loss rate $\dot{M} = 2.5 \times 10^{-7}$ $M_\odot$ yr^{-1} and terminal stellar wind velocity $u_{\rm wind} = 1000$ km s^{-1}. The wind velocity is consistent with UV resonance line observations (Howarth & Prinja 1989), but the mass–loss rate (required to give the correct stand–off distance for the proplyd bowshock, given our assumed value of $n_{\rm if}$) is lower than that derived by these authors.

In Figure 1, we compare our numerical results with the predictions of a simple analytic model for the position and shape of the bowshock. In this model, we assume that the (isothermal) proplyd flow is strictly radial, in which case, if the IF is D=critical, the radial dependence of the Mach number, $\mathcal{M}(R) \equiv u(R)/c_0$, is given implicity by $\mathcal{M}^{1/2} R = R_{\rm if} \exp[0.25(\mathcal{M}^2 - 1)]$ (Dyson 1968).

This flow is assumed to be in ram–pressure balance with the supersonic wind from the O star, so that $\rho_{\rm wind} u^2_{\rm wind} = \rho(R)_{\rm flow} u(R)^2_{\rm flow}$, which allows one to calculate the stagnation point where the bowshock crosses the symmetry axis. The shape of the shocked shell (assumed to be thin) is then found from consideration of the conservation of mass, momentum, and angular momentum following the formalism of Cantó, Raga & Wilkin (1996). The analytic model is only approximate because, although the shell of shocked proplyd flow material is thin, the region of shocked stellar wind is not. Nevertheless, there is close agreement between the position and shape of the shocked shell in our simulation and the prediction of the analytic model.

3. COMPARISON BETWEEN OBSERVED AND PREDICTED Hα INTENSITY

The numerical simulation gives the density, pressure and velocity throughout the grid. Using the density distribution we can calculate the Hα emission line intensity from

$$I_{\rm H\alpha} = \int \eta_{\rm H\alpha} \exp\left[-\tau_{\rm dust}\right] ds,$$

where $\eta_{\rm H\alpha} = \alpha_{\rm H\alpha} n^2/4\pi$ is the emissivity and $\tau_{\rm dust} = \tau_{\rm foreground} + \sigma_d \int n ds$ is the total dust optical depth, including both local and foreground contributions, σ_d is the mean effective dust extinction cross section per H atom, n is the number density and s is the distance along the line of sight. Here $\alpha_{\rm H\alpha} = 1.2 \times 10^{-13}$ cm^3 s^{-1} is the effective Hα recombination coefficient (case B). The foreground dust optical depth is taken to be $\tau_{\rm foreground} = 1.4$, derived from observed Balmer line ratios of the surrounding nebula (O'Dell 1998).

In Figure 2, we compare the intensity profile along a slit (shown by dotted lines in Fig. 1a) with the observed profile of the proplyd 167–317. Reasonable agreement of the relative brightness of the shock and the proplyd head is obtained using an inclination of 75° between the proplyd symmetry axis and the line of sight, together with an effective cross-section for internal dust of $\sigma_d = 2.4 \times 10^{-22}$ cm^2 H^{-1}. This is in good agreement with

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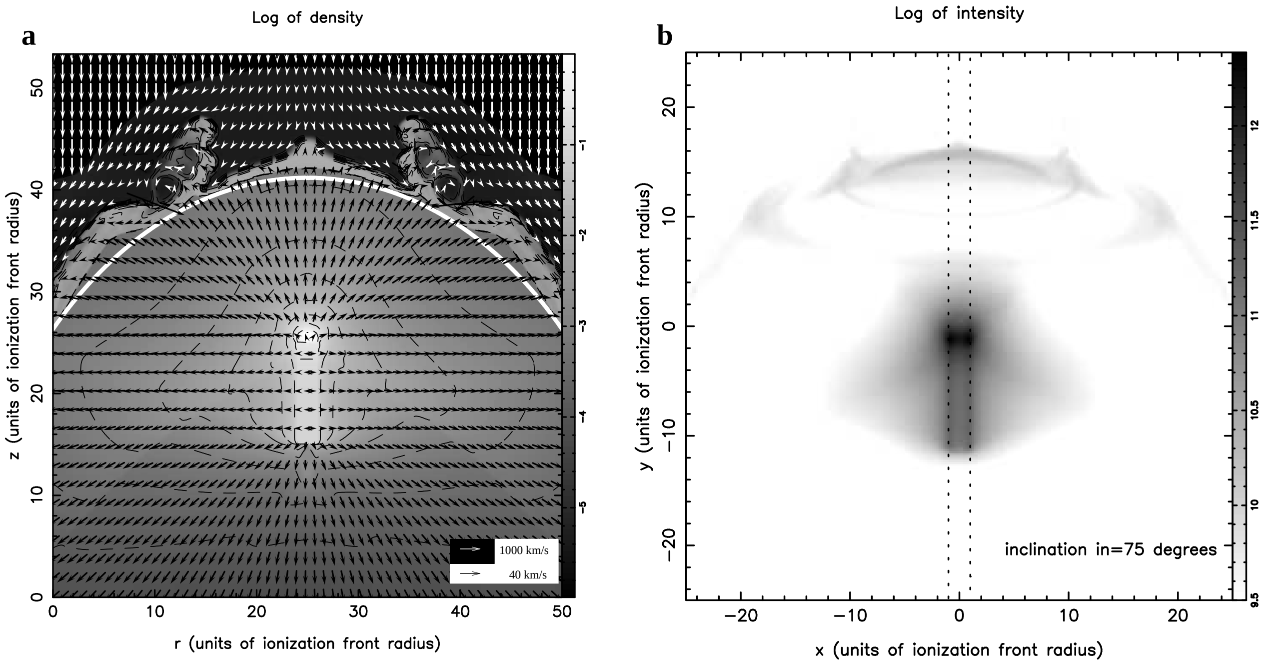

Fig. 1. (a) Hydrodynamical simulation of the interaction between two winds, calculated in 2–d cylindrical symmetry with a grid size of 600 × 600 cells. Arrows show gas velocity. Note that the velocity scale is different for the stellar wind (white arrows) than for the proplyd flow (black arrows). Grayscale shows the gas density in logarithmic scale. The white arc shows the analytical solution. (b) Map of intensity projected on the plane of the sky. The grayscale shows the intensity on a logarithmic scale, in units of photons s^{-1} cm^{-2} $ster^{-1}$.

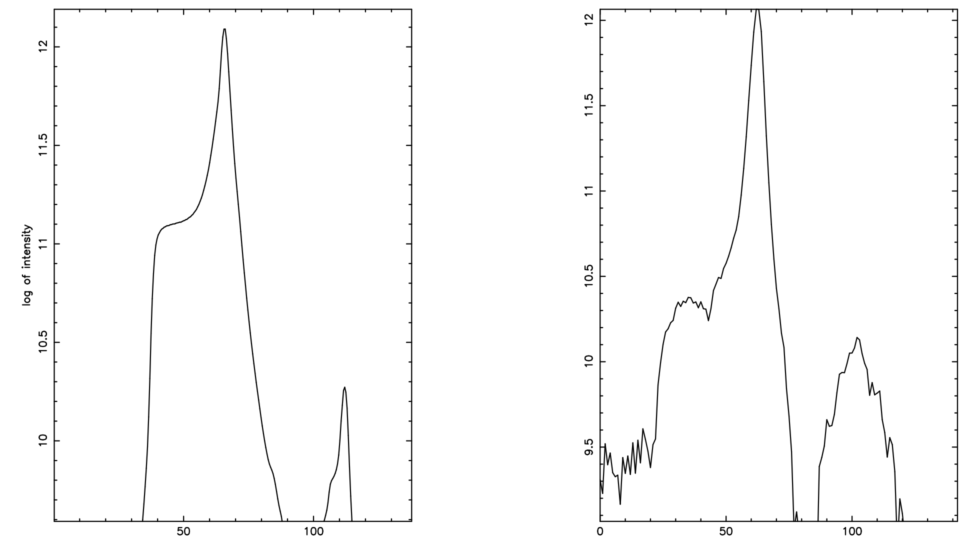

Fig. 2. Left panel shows the model intensity profile along the slice shown by dotted lines in Fig. 1. Right panel shows observed profile intensity. The vertical axis is log of intensity and the horizontal axis is distance in pixels ($0.0455''$).

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the canonical *extinction* cross-section for interstellar dust of 5×10^{-22} cm^2 (Savage & Mathis 1979), assuming an albedo of $\simeq 0.5$ and that scattering can be ignored to zeroth order.

4. CONCLUSIONS AND FUTURE WORK

Our hydrodynamic simulations show that the arcs seen in front of the inner proplyds in Orion can be plausibly interpreted in terms of the interaction between the proplyd photoevaporation flow and the supersonic wind from θ^1 C Ori. The brightness of the arcs in Hα can straightforwardly be explained by the photoionized spectrum of the shock–compressed gas shell, with a negligible contribution from shock excitation. We find no evidence for additional emission due to turbulent mixing between the dense shell and the hot, shocked stellar wind as suggested by Bally et al. (1998).

By consideration of the internal extinction at the base of the photoevaporation flow, we find that the visible dust opacity is not significantly different from that of the general warm ISM. Hence, we find no support for the hypothesis that the larger dust grains settle to the midplane of the accretion disks found within the proplyds, leading to their absence from the photoevaporation flow (Throop 2000). However, the uncertainties in the analysis are considerable, so the hypothesis cannot be ruled out. Further constraints on the dust properties in the photoevaporation flow will come from comparisons between our models and the 10 μm observations of Hayward, et al. (1994). We will also compare the kinematic predictions of our models with the high-velocity components seen in optical line profiles (Henney et al. 1997; Henney & O'Dell 1999) and perform three–dimensional simulations of three–wind interactions in proplyd binary systems.

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