

WHAT EXCITES FLIERS?

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ABSTRACT

The nature of the microstructures in planetary nebulae called fast low-ionization emission regions (FLIERS) remains somewhat of a mystery. These appear as ansae, jets, or pairs of symmetric knots on either side of the central star, are very small, and display highly supersonic motions. In this Letter we show that their properties can be understood as being the result of shocks in a strongly photoionized medium. Typically, the energy flux in the radiation field into the shock is 2 orders of magnitude higher than the flux of mechanical energy across the shock. These shocks appear to be associated with “exit nozzles” formed in the polar regions of the planetary nebulae, where the high-pressure photoionized gas escapes into the surrounding low-density interstellar medium.

Subject headings: ISM: jets and outflows — planetary nebulae: general — shock waves

1. INTRODUCTION

The existence of small, low-ionization features (ansae) in planetary nebulae (PNs) has been known since the pioneering work of Aller (1941). More recent work by Walker & Aller (1970) and Reay & Atherton (1985) showed that these knots have unusual excitation conditions if these are to be identified with ionization fronts and that they are also characterized by highly supersonic workers. The complete observational understanding of these objects, now called fast-moving low-ionization emission regions (FLIERS), has been developed recently by Balick and his coworkers (Balick, Preston, & Icke 1987 ; Balick et al. 1993, 1994).

In summary, FLIERS have the morphology of jets, knots, or strings of very small knots (e.g., López, Roth, & Tapia 1993), with typical sizes of approximately 0.01 pc, and they come in pairs that possess a high degree of bilateral symmetry about the central star. They are characterized by velocities of ejection from approximately 50 km s⁻¹ to even higher than 100 km s⁻¹, which gives them kinematic ages much smaller than for the nebula as a whole. Their masses are low, typically 10⁻⁴ to 10⁻⁵ M_⊙ and have hydrogen atom densities $\gtrsim 10^3$ cm⁻³. Their excitation is low, with prominent lines of [N II], [O I], and [S II] in the spectra. In particular, the strength of the [N II] has led to suggestions that the N/H ratio is strongly enhanced in the knots.

It has recently become clear that the mass ejection process in the asymptotic giant branch phase is not spherically symmetric; stellar wind tends to be slower and denser in the equatorial plane. As the central star becomes hotter, the velocity of the wind increases, and the flow is focused by the dense equatorial material toward the poleward direction. This is the so-called shaping of the PN in the two-wind model (Balick 1987). FLIERS might then be identified with either the tips of fast-moving lobes or as the working surface of a poleward-focused jet, analogous to those seen in the Herbig-Haro (HH) objects (Soker 1990; Soker & Harpaz 1992). The difficulty here is that the ionization structures observed (Balick et al. 1994) have the more highly ionized species seen closer to the central star, precisely the opposite to what is expected in these models.

A way out of this conundrum is to suppose that the FLIERS are formed within a poleward-directed jet itself. One possible mode of formation of such a jet is one where fast-moving stellar wind material, loaded with swept-up gas from the ionized gas from the PN itself, has been deflected poleward by the dense equatorial material. Approaching the FLIER knot in a roughly conically convergent flow, it passes obliquely through a conical shock front and cools to produce a dense sheet of gas with an outward velocity equal to the radial component of velocity in the convergent flow (Cantó 1980; Barral & Cantó 1981; Cantó, Tenorio-Tagle, & Różyczka 1988). This type of model is clearly favored by Cuesta, Phillips, & Mampaso (1993). Frank, Balick, & Livio (1996) suggest that the flow was set up earlier in the lifetime of the PN, when the stellar wind from the nucleus was slower, since the material in both the convergent flow and the primary wind shock must be shocked at a velocity lower than about 150 km s⁻¹. If this is not the case, these shocks become nonradiative, setting up a bubble of hot material either within the body of the young PN or else beyond the region of convergence. Low shock velocities in the convergent flow are favored when the angle of convergence is small, resulting in a highly oblique conical shock (Cantó et al. 1988). However, an alternative picture might be one in which mixing and mass-loading of the stellar wind with the ionized material has occurred in the flow, which would allow cooling of the hot shocked stellar wind material, and which would produce heavier and slower flows into the convergent region. In this model, cooling convergent flows could survive to a later stage of PN evolution where the stellar wind is faster.

An alternative model is one in which a confined jet is formed and which acts as an acoustic wave guide to support a set of self-excited modes (Payne & Cohn 1985). This model has the advantage of being able to produce strings of knots, but a coherent jet needs to be formed first, possibly through the convergent flow model discussed above.

Both of these models produce oblique shocks in the outflow and, since the shocks can be relatively weak, can allow for the preservation of an appreciable portion of the outflow velocity of the stream that gives rise to them. This offers a way to explain the high outflow velocities that are observed in the FLIERS.

Although such FLIER shocks would be physically analogous to the shock structures seen in HH objects, it should be

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recognized that the spectra produced by such shocks would be quite different than those seen in HH objects. The presence of a powerful photoionizing source of high temperature both profoundly modifies the preshock ionization conditions and provides a great deal of photoionization heating in the postshock gas. However, the geometry of such shocks is favorable in that the direction of flow of material through the shock is the same as the direction in which the photons from the central star are moving. This allows the radiation field to be treated in the downstream-only approximation, which leads to a number of important computational simplifications. In this Letter, I provide a simple parameterization of the physics and show that FLIERs can be qualitatively understood as photoionized shocks in which the flux of mechanical energy is much less than the photon energy flux across the shock front.

2. PHOTOIONIZED SHOCK MODELS

The problem of photoionized shocks is characterized by a number of important dimensionless parameters. First, let us define the shock velocity as V . If the speed of sound in the photoionized preshock gas is c_{II} , then the Mach number of the shock is $\mathcal{M} = V/c_{\text{II}}$. In a simple photoionized gas, the state of ionization (and therefore the emission-line spectrum) is largely determined by the ionization parameter, U , the ratio of the number of photons passing through a unit area per second, divided by the density of the gas (taken here as the hydrogen density in units of cm^{-3}) multiplied by the speed of light. This dimensionless parameter can be defined in the preshock gas:

$$U_1 = F/c\langle hv \rangle n_1, \quad (1)$$

where F is the photon energy flux through the shock, and $\langle hv \rangle$ is the mean energy of the ionizing photons. Let us assume that the postshock gas can cool to a point where it is once again in photoionization equilibrium with the radiation field, and let us further assume that the temperature of this plasma is the same, so that the shock structure can be regarded as isothermal. The ionization parameter in this postshock plasma is therefore the preshock ionization parameter divided by the compression factor across the shock. In the absence of magnetic pressure support in the postshock plasma, therefore,

$$U_2 = F/c[\mathcal{M}^2 + 1]\langle hv \rangle n_1. \quad (2)$$

The value of this postshock ionization parameter is very important to the shock structure, since it determines whether a region that is in photoionization equilibrium can exist in the postshock region. If it is larger than about 10^{-5} , then the plasma can pass through a region of photoionization equilibrium where it absorbs the residual radiation field from the star before passing through a recombination front and cooling to a low temperature. For U_2 much less than about 10^{-5} , the radiation field is not strong enough to allow a region of photoionization equilibrium to be formed behind the shock, and the gas passes immediately from the cooling zone behind the shock into the recombination zone. Since the gas passes through the shock and then recombines, the structure that is formed is quite unlike that of a normal ionization front, where the sense of the flow is opposite, from the unionized state to the ionized state.

Another dimensionless parameter that is obviously impor-

tant in our problem is the ratio of mechanical energy flux to photon energy flux across the shock η :

$$\eta = \dot{E}_{\text{mech}}/\dot{E}_{\text{phot}} = \mu m_{\text{H}} n_1 c_{\text{II}}^3 \mathcal{M}^3 / 2F. \quad (3)$$

Equations (2) and (3) imply that for shocks with moderate Mach number,

$$U_2 = \mu m_{\text{H}} c_{\text{II}}^3 \mathcal{M} / 2\eta c \langle hv \rangle = \kappa (\mathcal{M} / \eta). \quad (4)$$

Since the sound speed in the ionized plasma is always of the order of 10 km s^{-1} , the value of the constant κ is determined primarily by the effective temperature of the central star. For a star with $T_{\text{eff}} \sim 70,000 \text{ K}$, $\kappa \sim 2.5 \times 10^{-6}$. Therefore, the condition $U_2 \lesssim 10^{-5}$ implies that shock-induced recombination in the postshock plasma will occur for $(\mathcal{M}/\eta) \lesssim 4$. The implication of this inequality is that, for reasonably strong shocks, shock-induced recombination requires the mechanical energy flux across the shock to be comparable to the photon energy flux through the shock. In all other cases, the primary effect of the shock is simply to lower the ionization parameter in the postshock plasma.

2.1. Modeling the Emission-Line Spectrum

The shock/photoionization code MAPPINGS II (Sutherland & Dopita 1993; Dopita & Sutherland 1995, 1996) is perfectly suited to the problem of computing the emission-line spectrum of shocks illuminated by an external photoionizing source. In the PN and the FLIERs observed spectroscopically by Balick et al. (1994), He II is absent, which implies that the effective temperature of the ionizing stars is less than $90,000 \text{ K}$. On the other hand, the strength of the [O III] $\lambda 5007/\text{H}\beta$ ratio implies $T_{\text{eff}} > 50,000 \text{ K}$. Since FLIERs are outer structures of PN shells, the radiation field reaching the FLIER will have been modified by absorption in the nebula. Therefore, for general modeling purposes, a blackbody spectrum with $T_{\text{eff}} = 70,000 \text{ K}$, modified by a nebula producing an optical depth at the Lyman Limit, $\tau = 3$, has been adopted. The MAPPINGS II models use the solar abundance set given by Dopita & Sutherland (1996). A grid of models with $\mathcal{M} = 2, 3, 4$, and 6 and with $\log U_1$ in the range -2 to -5 (in steps of 0.5) was computed. These models correctly treat the time-dependent cooling, dynamical, and photoionization problems in the downstream-only approximation. The initial hydrogen density was held constant at 100 cm^{-3} for all of these models.

For much of the range of parameter space covered by the grid, $\eta \ll 1$, so these shocks are energetically dominated by the radiation field. Higher values of \mathcal{M} are unlikely to be encountered, since radial velocities of FLIERs do not often exceed 50 km s^{-1} . Thus, the parameterization given in the previous section implies that the emergent spectra will tend to be more or less invariant in terms of U_2 . In Figure 1, we plot a number of important and easy to observe line ratios of oxygen, sulfur and nitrogen against $\log U_2$. Models to the left of the gray line in each plot are energetically dominated by the shock, and this is also the region where shock-induced recombination will occur. Thus, this is also the region where the parameterization of the models in terms of $\log U_2$ becomes inappropriate. It is therefore to be expected that the line ratios in Figure 1, particularly the [O III] $\lambda 5007/\text{H}\beta$ line ratio, diverge from a tight sequence in this portion of the diagram.

Note that, for much of the range of $\log U_2$, the [N II] $\lambda 6584/\text{H}\alpha$ line ratio is of order unity. This implies that the observed strength of the nitrogen lines in FLIERs can be explained

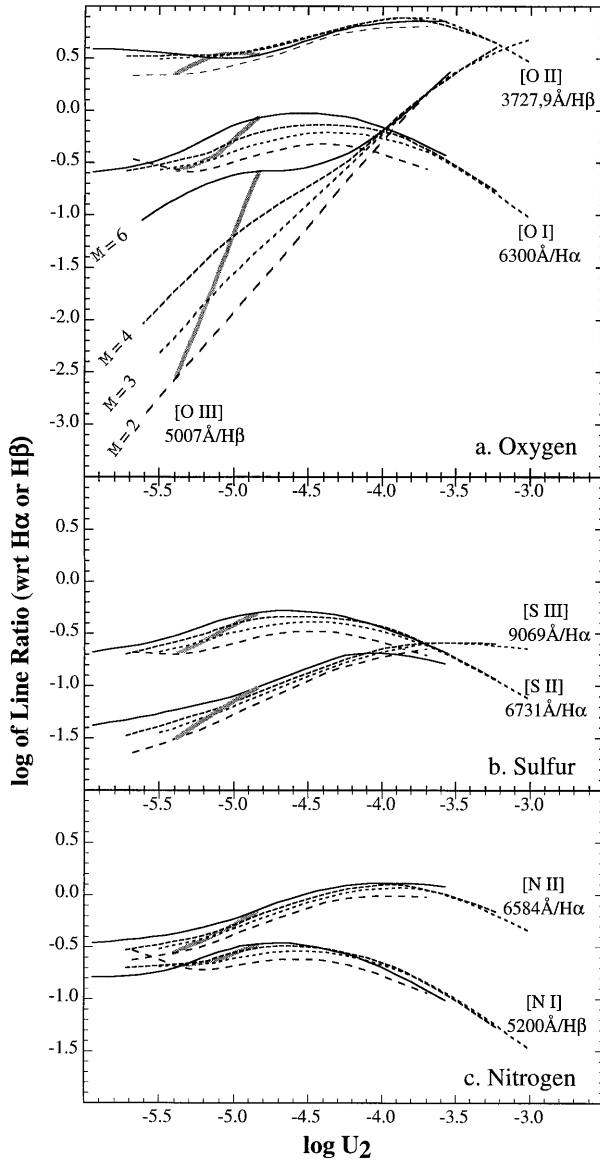


FIG. 1.—The variations of a number of line ratios involving ions of (a) oxygen, (b) sulphur, and (c) nitrogen are shown as a function of ionization parameter in the postshock gas for FLIER shock sequences of different Mach number, as marked on the [O III] $\lambda 5007/\text{H}\beta$ line ratio sequences. Regions to the left of the thick gray lines are dominated by the mechanical energy flux through the shock, while regions to the right of these lines are photon energy flux dominated.

without assuming any enhancement of the nitrogen abundance over solar values. Indeed, the line ratios predicted in these models can be used to derive likely values of $\log U_2$ in the FLIERS observed spectroscopically by Balick et al. (1994). For the line ratios shown in Figure 1, with the exception of [O II] $\lambda 3727/\text{H}\beta$, which is more strongly affected by collisional de-excitation than in these models, [N I] $\lambda 5200/\text{H}\beta$, which is a highly uncertain measurement, and [S III] $\lambda 9069/\text{H}\alpha$, which is not observed, we deduce quite consistent values of $\log U_2$ in the range -3 to -3.3 , where $\log \eta \leq -2$.

Such values of $\log U_2$ imply either that the shocks have a low Mach number or a high initial ionization parameter. The second condition would favor a high emission measure of the

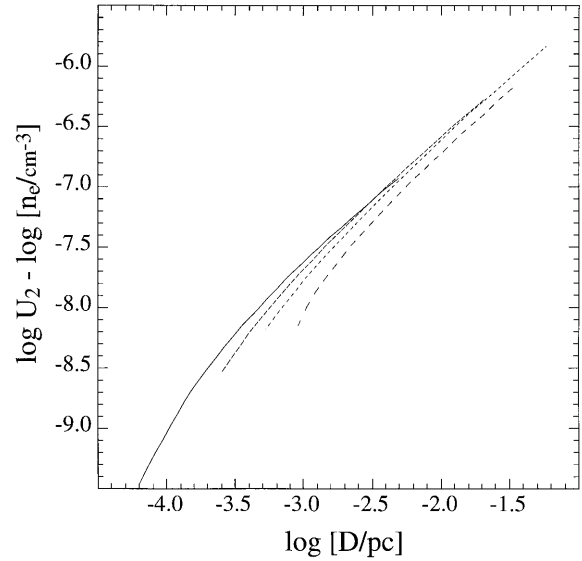


FIG. 2.—The thickness of the photoionized shock structures as a function of the ionization parameter in the postshock gas, and the postshock electron density in the [S II] emitting region. The FLIER parameters are all consistent with sizes of the order $\log (D/\text{pc}) \sim -2$.

FLIER relative to the gas entering the shock, i.e., high contrast between the FLIER and its surroundings.

The electron temperatures observed in FLIERS are consistent with those predicted by these models ($8600 \text{ K} > T_e[\text{N II}] > 6600 \text{ K}$). The predicted size of a FLIER can be obtained from the electron densities of the ansae ($n_e \sim 1000\text{--}2000 \text{ cm}^{-3}$) derived from the [S II] lines and the value of $\log U_2$ implied by their spectra. This is because in both kinetic energy-dominated and photon-dominated shocks, the thickness of the ionized region scales inversely as the electron density. This is shown in Figure 2, where the thickness of the computed shock structure $\log (D/\text{pc})$ is plotted against $\log U_2 - \log (n_e/\text{cm}^{-3})$, where the electron density is that in the [S II] emitting region. Since $\log U_2 - \log (n_e/\text{cm}^{-3}) \sim -6.5$, our models imply $\log (D/\text{pc}) \sim -2$, in excellent agreement with the observation.

3. CONCLUSIONS

The excitation, temperature, size, and electron density of FLIERS can all be understood if these are shocks in which the energetic flux of ionizing photons into them is about 2 orders of magnitude higher than the mechanical energy flux through the shock itself. In this case, the shock serves to compress the gas, lowering the ionization parameter in the postshock photoionized region and enhancing the emission lines of low excitation.

Since in these models the velocity vector of the material passing through the shock and the photon flux vector are both outwardly directed with respect to the central star, these shocks must be either oblique or traveling in order to ensure that the postshock gas remains with the large outflow velocity observed with respect to the central star ($\sim 50 \text{ km s}^{-1}$). FLIERS cannot therefore represent bow shocks around ejected “bullets,” or even the working surface of jets acting against the interstellar medium. Rather, they must represent shocks that are internal to outflows, either resulting from convergent surface flows toward the apex of the ionized region

(Barral & Cantó 1981; Cantó et al. 1988; Frank et al. 1996) or through weak internal shocks in jets set up by self-excited reflective modes (Payne & Cohn 1985). In this case, the knots will form a string with a spacing, s , to jet diameter, d , ratio that is related to the Mach number in the jet and the density contrast between the interior of the jet and its surroundings:

$$s/d \leq (0.6-0.8) \frac{\mathcal{M}}{1 + (\rho_{\text{int}}/\rho_{\text{ext}})^{1/2}}, \quad (5)$$

where the constant 0.8 applies to the first reflection pinching mode, and the 0.6 applies to the helical Kelvin-Helmholtz pinching mode (eq. [4.1] of Payne & Cohn 1985). In the case

of the remarkable string of knots observed in Fleming 1 by López et al. (1993) and López, Meaburn, & Palmer (1993), this almost certainly has to be their mode of generation, since all the knots are characterized by large outflow velocities.

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