The hydrodynamics of aspherical two-wind configurations

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1. Stardeath

The life of a star is an incessant struggle between gravity and gas pressure. The self-gravity of a star's mass pulls it together; the star doesn't collapse as long as it can find a source of counteracting pressure. At first, the pressure of the hot gas in the star suffices, while the heat from the nuclear fusion of hydrogen into helium provides enough energy to make up for the radiation lost for ever from the surface of the star. Later, this gas pressure can still be maintained for a while when helium fuses into carbon. But ultimately the star runs out of nuclear fuel, losing its main defense against implacable gravity. Thus, finally the stellar core collapses.

In stars that contain more than eight times the mass of the Sun, this collapse is so violent that the star explodes as a supernova, outshining the whole Galaxy for a few months. Smaller stars, such as our Sun, also suffer core collapse, but this is a more gradual process. For a while such a little star tries to scratch some energy out of a razor-thin shell of fusing hydrogen and helium. But this is like burning wet grass: it provides little energy and the fusion flame flickers irregularly. During this so-called "AGB phase", the outer envelope of the star swells up and starts to lose mass which spreads into interstellar space. As the gas cools down, heavy atoms in the outflowing gas, such as carbon and silicon, clump together and form dust grains: the star surrounds itself with an expanding cloud of gas and soot.

Then, in a last ten-thousand-year gasp, so brief compared with the star's ten-billion-year lifetime, the dying stellar core blows off a fast, tenuous stellar wind, moving with a speed up to thousands of kilometers a second. Ahead of it lies the dense, slow, fossil envelope that was laid down during the AGB phase, trundling on at ten to 20 kilometres a second.

These two winds meet violently. A steep shock wave crashes ahead into the slow envelope, while a reflected hot shock moves upstream into the oncoming fast wind. A steep contact discontinuity separates the two winds. Across this contact surface, the pressure is in equilibrium but the density jumps by three or four powers of ten.

The result is a *planetary nebula*, a hollow shell of brilliantly luminous gas surrounding the dying stellar core, which will – in a million years or so – be a dead white dwarf.

2. Aspherical Nebulae

So we find that planetary nebulae (PN) are bubbles blown by a tenuous, fast stellar wind into a dense, slow, fossil red giant envelope (RGE). This interacting-winds model is quite complete in spherical geometry, but not all PN shells are spherical. Quite the contrary: the great majority shows a pronounced bipolar or spindle-like appearance. The research question with which Bruce Balick confronted me, back in 1984, was: *Why are most PNs bipolar, what are the (hydrodynamical) mechanisms responsible for this, and – once we understand this – what can bipolar PNs do that spherical ones cannot?*

Balick (1987, 1988) suggested that the interacting-winds model in two dimensions might explain the shapes of nearly all PNs. He hypothesised that the RGE is expelled with cylindrical symmetry and that the density is higher at the equator than at the poles. The PN morphology and its evolution is then purely a consequence of the mass distribution in the RGE and the properties of the fast stellar wind.

3. From Analytical to Numerical Progress

So I set to work on analytical models for aspherical PNs. These have been quite successful in describing the propagation of the outer shock of a two-wind configuration. I used a generalization of the work by Kompaneets (1960; Balick et al. 1987, Icke 1988, Icke et al. 1989), in which the wind is supposed to generate a uniform pressure inside the expanding bubble. The method is easy to apply and shows the generic features of the outer shocks clearly. But enough about this: the context here is numerical work! Suffice it to say that the observational appearance of the outer shock is now well understood. However, what happens inside that shock requires numerical computations.

We are dealing with a formidable hydrodynamical problem (Icke 1991). The differences between the slow and the fast winds amount to density jumps of the order of 3000 and velocity jumps in excess of 200.

Such extreme circumstances require extraordinarily cautious numerical work. The snag is residual numerical diffusion. Icke (1991) demonstrated these effects by deliberately degrading a second-order hydrocode, of a type with small diffusive errors, so that it smoothly approached the behaviour of a first-order code where numerical diffusion is large. The second-order errors in this degraded code cause numerical diffusion of gas from the huge contact discontinuity between the fast wind and the RGE. This produces unphysical results: the outward flow from the central star is smothered by the spurious inward momentum flux of the numerical diffusion.

A word to the wise about good numerical technique: if you are interested in making real models instead of *ad libitum* sketches on overhead transparencies, fine; but leave the design of hydrocodes to the experts, just like you would the building of a telescope. There are plenty of excellent numerical schemes (e.g. Woodward & Colella 1984, Boris & Book 1973, 1976, Boris et al. 1975, Zalesak 1979, Van Leer 1984, Roe 1986, Icke 1991, Eulderink 1993, Eulderink & Mellema 1994). If at all possible, cadge a code from someone else. Or use their results for post-processing.

The interacting winds produce the usual triple discontinuity: an inner (reverse) shock surrounding the central source; an outer shock propagating into the RGE; and a contact discontinuity separating the two. The outer shock conforms to the analytic expectations. The inner shock develops in a strongly transient way, due to a reflection off the equatorial belt; during this evolution, the shock deflects and focuses the fast wind.

The equator-to-pole density contrast mostly determines the timescale on which a strongly aspherical outflow pattern is established. The contact discontinuity and the flow behind the leading shock show two types of patterns, depending on the value of opening angle of the RGE. At wide angles (quasi-toroidal cloud) one finds elliptical to peanut-shaped outer shocks, inside of which the aspherical structure is hardly apparent. The flow behind the outer shock on the symmetry axis has the appearance of an ascending vortex or mushroom cloud. The inner (reverse) shock is strongly aspherical and time-dependent.

Steep opening angles describe funnel-like RGE's which produce fairly spherical inner shocks, with jet-like structures extending above them. These form remarkably quickly and persist while flowing almost parallel along the axis, occasionally crossed by an X-shock, and finally protruding into a cap formed by the outer shock. The high degree of autocollimation arises as relatively cold gas is entrained into the flow at the point where the outer shock makes a sharp inward cusp. This cool gas forms a confining chimney, a turbulent cocoon, which confines the hot gas as a jet near the axis. At the head of the jet the gas curves outward and backward, forming a backflow which helps to stabilize it against the sideways pressure in the jet (Fig.1). The flow near the symmetry axis terminates in shocks of the type seen in cylindrical jets which emanate from a perfectly collimated orifice (Norman et al. 1983, Wiita 1991).

In our case, however, it is the flow itself which does the collimating through the combination of inertial confinement of the chimney and the pressure of the backflow gas outside it: parallel flow is not imposed as a boundary condition. The mechanism is quite different from that introduced by Blandford and Rees (1974).

The contact discontinuity is usually quite corrugated and in most cases it is downright unstable. This leads to the formation of a mixing zone between the hot bubble gas and the RGE material.

4. Including more physics

The luminosity of planetary nebulae does more than make them beautiful in the sky: radiation is important in their evolution, too. Therefore, the most urgent item to include is a radiative exchange term in the energy equation. Momentum deposition is of lesser concern, and will not be considered here, although I note that radiation pressure is likely to be important in other applications of the aspherical two-winds mechanism, such as line pressure in massive young stars and in active galactic nuclei, and pressure on dust in very young PNs and in young low-mass stars.

It is easy to incorporate radiative transfer after a purely hydrodynamical computation run, because the radial-only approximation (Icke, Gatley & Israel 1980) can be used here, even in the presence of dust. This is particularly easy by means of the analytical line emissivity functions introduced by Balick et al. (1993). However, this form of post-processing does not affect the dynamics and can only be used as a first guess of what the PN models would look like in various continuum bands or lines. Realistic radiation hydrodynamics in PNs has been initiated by Garrelt Mellema and Adam Frank; this space is too small to contain their numerous contributions (Mellema et al. 1991; Frank 1993, 1994; Mellema 1993a,b,c, 1994; Frank et al. 1993; Frank & Mellema 1994a,b).

Fig.1 Numerical results of a shock propagating in a red giant envelope. The frame shows logarithmic greyscale of the density. Black is highest, white is lowest. Check my home page for images like this at http://www.strw.LeidenUniv.nl/~icke/. Compare with observed bipolar nebulae, such as can be found on http://www.astro.washington.edu/balick/ or on http://www.stsci.edu, in particular http://www.stsci.edu/pubinfo/PR/96/07.html

5. Getting ambitious

In the near future I intend to apply the interacting-winds formalism to flow regimes other than those that occur in PNs. Such applications include the wind-ring interaction that apparently takes place in the supernova SN 1987A. Another interesting example where biconical flow might occur is the Homunculus of η Carinae (cf. Icke 1981). The 'inertial confinement' mechanism for the formation of gaseous jets should apply to all situations that are geometrically similar to the PN case, ranging from young stars to active galactic nuclei.

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