BASIC PROBLEMS OF PLANETARY NEBULA GAS DYNAMICS

J.E. DYSON
Department of Astronomy, University of Manchester, Manchester M13 9PL, U.K.

Abstract

Planetary Nebulae result from the interaction of fast winds and radiation fields with slow ejecta produced in the late stages of evolution of moderately low mass stars. We review the basic principles of the interaction and describe some of the modifications needed to produce realistic models for comparison with observational data. The present status of numerical modelling is discussed and some important problems outlined.

1 Introduction

Planetary nebulae (PNe) provide an exciting opportunity for the study of high speed gas dynamics under conditions far removed from terrestrial. The interactions taking place in them are of importance both intrinsically and for other areas of astrophysics. These interactions involve a rich variety of physical phenomena whose elucidation can come only from combined observational and theoretical studies.

Most theoretical investigations of PNe predicate the 'Interacting Winds' model of Kwok *et al* (1978). A fast ($u_F \geq 2000$ km s^{-1}) wind from the PNe nucleus interacts with slower ($u_s \approx 10$ km s^{-1}) ejecta from previous red giant (RG) and asymptotic giant branch (AGB) phases of the nucleus' evolution. The ejecta are swept up into a shell by the fast wind and photoionized by the radiation field of the nucleus. In general terms this model is strikingly successful; the global properties of PNe (e.g. sizes and expansion velocities) are well reproduced. However, the wide range of PNe morphologies and properties and great complexities revealed in the detailed study of specific objects, demand considerable elaboration of this basic picture. In order to construct more realistic theoretical models, a number of areas demand clarification. Firstly, conditions in the slow ejecta need specification. Molecular line observations of AGB and post-AGB objects (e.g.Olofsson 1992) show that the slow ejected envelopes possess complex density and velocity structure. Secondly, the behaviour of the sources of momentum, energy and mass input which interact with the slow ejecta must be known. Finally, it is necessary to include all relevant physical processes such as hydrodynamic mixing at interfaces. Given the often large uncertainties and parameter ranges in these areas, it is hardly surprising that PNe are so varied in form.

R. Weinberger and A. Acker (eds.), Planetary Nebulae, 299–306.
© 1993 *IAU. Printed in the Netherlands.*

https://doi.org/10.1017/S0074180900171037 Published online by Cambridge University Press

The comparison of models with particular objects is the only way forward, but is complicated by the effects of evolution. Even the simplest models demonstrate appreciable differences in structure and evolution when parameter values are varied within perfectly plausible ranges. Studies of the—in many ways analogous—object RCW 58 (a Wolf-Rayet nebula), show that unless comprehensive observational data is available, totally inappropriate (though superficially applicable) models may be used (e.g. Smith *et al* 1984, 1988; Hartquist *et al* 1986; Arthur *et al* 1992).

The emphasis in this review is on the physical consequences as different modifications to the simple models are made and on the relevance of the effects produced to observational data. The results of detailed numerical studies are discussed where appropriate.

2 Basic Models with Spherical Symmetry

The simplest model assumes constant mass ejection rates and velocities in the various stages of mass loss and a constant Lyman continuum output rate from the nuclear star. With characteristic parameters, most of the flow momentum initially resides in the AGB (or superwind) ejecta. The impact of the fast wind on the slow ejecta produces the familiar 'two-shock' flow pattern. Provided u_F is great enough ($u_F \gtrsim 1000$ km s^{-1}) *and* the shocked fast wind cools only by adiabatic expansion, a shell of compressed slow ejecta is driven outwards by the shocked wind pressure at constant velocity V_s, typically a few times u_s. The total momentum content in the flow is increased by a factor of a few. The shell is initially optically thick in the Lyman continuum and becomes optically thin at times in the range $10^{(3-5)}$ yr, i.e. spanning characteristic evolutionary time scales.

Significant effects can occur if even relatively minor variations are introduced into the model. For example, if there is a time delay between the end of the slow wind and the onset of the fast wind, the swept-up shell may be initially optically thin and later become optically thick. A low emission measure 'halo' of unshocked slow wind can form which persists for a few thousand years after the shell becomes optically thick (Kahn 1989).

Evolutionary models of the nuclear stars show that the winds and radiation fields gradually power up to their full terminal velocities and luminosities (Schönberner 1983; Pauldrach *et al* 1988). Kahn & Breitschwerdt (1990) and Breitschwerdt & Kahn (1990) allowed for this in a semi-analytic treatment of the early stages of PNe evolution, assuming a constant wind momentum output rate. The wind speed is initially low enough for the shocked wind to cool radiatively; the shell is driven by direct momentum transfer. The changeover to a pressure driven shell occurs at time t_* ($\approx 10^3$ yr) when $u_F \approx 150$ km s^{-1}. Complex events can be contained within this simple scenario. Ionization of the swept up shell becomes dynamically significant at a time t_i (generally $\leq t_*$). At times $t < t_i$; t_*, the shocked fast and slow winds are cool. For times $t_* > t > t_i$ the inner part of the shell is ionized, its increased pressure drives the stellar wind shock back towards the star, the outer shock accelerates and the neutral-ionized interface in the shell can become Rayleigh-Taylor (R–T) unstable. At times $t > t_*$, the now finite pressure of hot shocked fast wind drives a second shell into ionized previously shocked cool ejecta. This shell can trap the Lyman continuum and the previously ionized ejecta can recombine. The resultant pressure drop can lead to acceleration of the second shell and another bout of R–T instability producing cool small ($\ell \sim 10^{15}$ cm) fragments.

The role of R–T instability is important in this model and is an example of a physical

https://doi.org/10.1017/S0074180900171037 Published online by Cambridge University Press

process requiring careful investigation. Hartquist & Dyson (1987) argued that shell acceleration alone is not sufficient to cause shell fragmentation and that shells might reseal themselves by the ablation of gas off fragments as the hot gas flows round them; some additional mechanism (e.g. thermal instability) may be necessary for genuine fragmentation. Observational support for this view comes from data on filaments in the Vela Supernova (Meaburn *et al* 1988), and it remains an open question.

Purely radial variations in the density of the slow wind may be reasonably conjectured as a result of time dependent ejection, and may have important consequences. Molecular hydrogen line features with velocities exceeding 250 km s^{-1} are observed towards the protoplanetary nebula CRL 618 (Burton & Geballe 1986). Serious problems exist for shock accelerated models; molecules are dissociated even in magnetically moderated shocks of velocity $\geq$ 50 km s^{-1}. The ram pressure acceleration of coherent clumps is more magic than physics. Hartquist & Dyson (1987) have suggested that the re-acceleration of shells whose velocity has dropped for a time below 50 km s^{-1}, by the presence of suitably steep density gradients in the slow ejecta, may provide a way round these problems.

3 Effects of Non-Uniform Slow Winds

Because of the very high sound speed in the shocked fast wind, deviations of shell shapes from spherical symmetry are induced only by non-uniformity in the slow wind density distribution. Balick (1987) qualitatively demonstrated that many of the global features of PNe morphology (e.g. bipolarity) can be explained if there exists a density contrast between the polar and equatorial regions of the slow wind. There are several possibilities for producing such non-uniformity. Probably the most plausible involves the presence of a binary system (Morris 1987; Soker 1990; Soker and Livio 1990; Bond & Livio 1990; Soker 1992a). However there may have to be mechanisms involving single stars. Soker & Harpaz (1992a) have, for example, suggested that non-radial oscillation modes can lead to axi-symmetric mass loss towards the end of the AGB phase, producing greater asymmetry in the core regions of PNe than in the haloes. However, Soker & Harpaz (1992b) note that a companion is probably still necessary to excite non-radial modes.

Many general models have been calculated which include such variations, ranging from relatively simple quasi-analytic approaches (e.g. Kahn & West 1985; Ghanbari 1989; Henney & Dyson 1992) to detailed numerical modelling (e.g. Soker 1989; Soker & Livio 1989; Mellema *et al* 1991; Icke *et al* 1992). The quasi-analytic approaches have the merit of greater generality and many relevant physical processes can be included at least on an approximate level. Detailed numerical models face formidable difficulties (e.g. Icke *et al* 1992) due to the extreme variations in conditions in different regions of the flow. These models show many intriguing features, such as cocoon and jet-like features (Mellema *et al* (1991), but, as pointed out by these authors, the assumption of axial symmetry encourages caution in the interpretation of them. Three-dimensional calculations are essential.

Generally, these models have supported Balick's (1987) proposals, but to compare models with actual objects, the detailed ionization structure must be solved along with hydrodynamics. Recent calculations by Mellema and by Frank (this meeting) have made considerable progress in this aspect. Both morphology and internal kinematics are essential to discriminate between models. Chu (1989), for example, has noted examples of PNe which have a core-halo morphology where the less bright outer halo appears to expand as

https://doi.org/10.1017/S0074180900171037 Published online by Cambridge University Press

fast or even faster than the inner core. This is hard to explain on the simple interacting wind model. Finally, all such calculations invoke smooth distributions of slow ejecta and, as discussed below, flows in clumpy media behave very differently.

4 Flows in Clumpy Media

PNe appear clumpy on a variety of scales in both ionized and neutral gas. Ionized features have scale sizes from $\ell \sim 10^{15}$ cm (e.g. in NGC 7293) to $\ell \sim 10^{16-17}$ cm (e.g. ansae). A substantial fraction of the total PNe mass can reside in molecular bearing material which is fragmented down to scales limited only by instrumental resolution (Bachiller *et al* 1990; Forveille & Huggins 1991; Huggins 1992). There are two extreme possibilities for the origin of these fragments; either they are primordial or generated during the interaction processes taking place. We concentrate on the former possibility here.

In general, the clumps would be embedded in an interclump medium. Their importance is four-fold. Firstly, gas flow around clumps ablates material into the flows and the subsequent mass injection can affect flow physics, chemistry and dynamics (Hartquist *et al* 1986; Arthur *et al* 1992). Secondly, the clumps can determine where the incident wind is shocked. If the clumps are not too numerous, the shock position is essentially determined by the interclump medium and it moves outwards in a similar manner to the case of smoothly distributed gas; however, mass loading behind the shock can profoundly affect the post-shock flow (Hartquist *et al* 1986; Arthur *et al* 1992). If, on the other hand, the clumps are very numerous, the interclump material plays little role in determining the position of the wind shock. The wind is decelerated primarily in bow shocks around the clumps. If the clumps last long enough, the positions at which the wind is shocked either remain spatially fixed or move outwards with more or less the clump velocities. This latter situation may be relevant to NGC 7293 where many small clumps of primordial origin could be present (Dyson *et al* 1989). Thirdly, the coexistence of the clumps and global flows results in interface (or boundary layer) formation. Very important effects such as the enhancement of radiative losses, can occur there. The study of such interfaces is a major area of interest in a wide variety of astrophysical environments (Hartquist & Dyson 1988, 1992). Finally, structures intermediate in scale size between the boundary layers and the global flows may produce observable features in PNe (Dyson *et al* 1992–Section 5).

Many qualitatively different flows can be produced in the shocked wind region as a result of mass loading. The situation where there are relatively few mass loading centres has been discussed in the context of RCW 58 (Smith *et al* 1988). As noted above, however, the structure of NGC 7293 suggests the presence of many small distributed clumps. It is likely then that there is very effective enhanced radiative cooling in the shocked stellar wind gas and it may percolate ballistically through the clumps. If the rate of mass ablation per unit volume into the shocked flow is constant and ablated mass dominates the flow it is straightforward to show (Dyson & Hartquist 1992) that the gas flow velocity $v \propto r^{-3}$ and density $\rho \propto r^4$, where r is the distance from the star. This flow matches at a contact discontinuity to interclump material swept up by the outwards facing shock (possibly after going through another shock). The appearance of such a flow depends crucially on where the radiated energy originates. If the entire bubble radiates as a result of photoionization by the stellar radiation field, the emission will be concentrated in a sheet like structure near the contact discontinuity if it largely originates in the interclump flow; on the other

https://doi.org/10.1017/S0074180900171037 Published online by Cambridge University Press

hand it will be more uniformly distributed (though clumpy on a small scale) if it originates at clump flow interfaces. The mixing of cold clump and hot shocked wind gas may lead to enhanced soft X-ray emission from intermediate temperature ($\sim 10^6$ K) gas (cf. Kreysing *et al*, these Proceedings). Whatever the details, it is clear that clumps can significantly affect the structure and dynamics of PNe.

5 Specific Structural Features of PNe

5.1 Haloes

The bright cores of many PNe are surrounded by extended envelopes with radii extending up to 0.9 pc in extreme cases (Chu *et al* 1987; Chu 1989; Frank *et al* 1990; Balick *et al* 1992). The envelope may give information on the ejection history in the slow wind phase (Frank *et al* 1990; Balick *et al* 1992), and provide constraints on the models for the formation of the structure (Soker *et al* 1992). Balick *et al* (1992) divide the envelopes into shells which often have roughly linearly outwards decreasing brightness distributions and haloes which are of low brightness and always limb brightened. Limb brightening can be the result of halo confinement by some external medium of adequate pressure (Frank *et al* 1990). This could either be RG ejecta (Balick *et al* 1992) or the local interstellar medium (Borkowski *et al* 1990; Soker *et al* 1991). Differentiation between the two possibilities is clearest for cases where the bright halo rims have a bow shock morphology, suggesting the motion of the star relative to an ISM (Soker *et al* 1991). However, none of the calculations so far made has included dynamical effects associated with photoionization. Generally haloes are less elliptical than the inner cores. This may simply be a hydrodynamic effect since flows expanding with velocities about equal to their internal sound speed tend to even out their pressure (or—for isothermal flows—density) gradients (Balick *et al* 1992). Alternatively, the later stages of slow wind ejection may be much more non- spherical (e.g. Plait & Soker 1990; Soker & Harpaz 1992a).

The kinematic structures of haloes are varied. Chu (1989) has noted cases where the halo appears to expand faster than the core. She also noted others where the simple dynamical timescale is greater for the core than the halo. Wang (1992) has suggested that the interaction of a fast wind with a constant velocity but time varying asymmetric slow wind can lead to fast expanding lobes with an apparent lifetime less than the slower moving waist regions. Another possibility (Dyson 1992; Dyson & Hartquist 1992) is that the cores are extremely clumpy and the stellar wind is so mass loaded that it exists transsonically from the core. Isothermal transsonic flows can accelerate to mach numbers of two or three over a reasonable range of halo to core radius.

As a specific example, NGC 6720 poses particular problems (Balick *et al* 1992). Molecular emission from H_2 occurs from shells apparently within the ionized haloes. The molecular gas expands more rapidly than the surrounding ionized gas, thus ruling out inclined bipolar flows. Balick *et al* (1992) suggest two possibilities. Firstly, the core is clumpy and the exterior halo is photoionized by UV photons which leak through between clumps. In this case the halo could not be mass loaded wind whose velocity should not drop much below that of the core clumps. Alternatively, if the more recently ejected core is optically thick, the halo could be in the process of recombining (cf. Section 2). In either case, the core gas must be ejected faster than the halo gas.

https://doi.org/10.1017/S0074180900171037 Published online by Cambridge University Press

Mass loaded flows exitting from clumpy cores can have interesting consequences if they interact with pre-existing halo material. Three PNe with extended haloes have halo electron temperatures (from [OIII]) up to 50% higher than the core temperatures (Middlemass *et al* 1990). Dyson (1992) has suggested that these are produced as a moderate (2–3) mach number mass loaded flow shocks against condensations in a halo. Forbidden line emission is enhanced by the temperature increase, but because of the bow shock geometry, the line widths would be much lower than the pre-shock flow velocities. Meaburn *et al* (1991) have shown that the [OIII] lines over a bright condensation in the halo of NGC 6543 indeed have low line widths.

5.2 Ansae

Some elliptical PNe have bright knots or 'ansae' along the major axis on either side of the nucleus. They appear to contain neutral material since low ionization lines and molecular emission is associated with them. They can be inside or outside the main body of nebular emission; usually they are moving outwards relative to the bulk of the nebula. It is tempting to associate them with the tips of fast moving lobes in bipolar flows. However, numerical calculations (e.g. Mellema *et al* 1991) do not produce suitable structures. A jet-like origin (Soker 1990) where the ansae are produced at the working surface of a jet (cf. HH objects) has many attractions. Lopez *et al* (this meeting) have shown a particularly striking jet-like structure in FG 1 (He2-66).The collimation of jets from a rotating star has been discussed by Soker (1992b). However, it depends critically on the very badly understood distribution of angular momentum within the star. Jet-like activity is known to occur in symbiotic stars (e.g. R Aquarii). Links between symbiotic stars and at least some PNe are becoming apparent (Lutz *et al* 1989). It may be that some ansae or jet-like features in PNe are formed by whatever (badly understood) processes are operative in R Aq or in the young stars associated with HH objects.

5.3 Small Scale Structure

The origin and morphology of small scale clumps in PNe are of great interest. Mechanical processes such as R–T instability (Section 2) may provide a way of introducing them into PNe. Alternatively they may be primordial and reflect the presence of very clumpy mass ejection (Olafsson 1992; Dyson *et al* 1989). NGC 7293 possesses many small 'cometary' globules at the inner edge of the ionized region. The globule parameters inferred by Meaburn *et al* (1992) from dust absorption are in excellent agreement with those required for the globules to be of primordial origin (Dyson *et al* 1989). The globules have long tails with widths about equal to the globule head diameters. Such a 'wind-swept' appearance argues for some type of stellar wind interaction. This cannot be due to the interaction of a supersonic wind with a globule (Dyson *et al* 1992). The central star of NGC 7293 has evolved too far to have a fast wind, and the interaction of supersonic streams with embedded gas sources produces very broad tails (Dyson *et al* 1992). A more likely possibility is that the globule is immersed in subsonic hot shocked wind gas which has been 'bottled up' following the fast wind phase. Small pressure differentials produced as the hot gas leaks out of the core are responsible for the confined long tails (Dyson *et al* 1992).

https://doi.org/10.1017/S0074180900171037 Published online by Cambridge University Press

6 Conclusions

Considerable progress has been made in understanding the general gas dynamical processes occurring in PNe. However, many challenging areas remain. The development of 3-D numerical codes which incorporate radiative heating and cooling is a prime candidate. There are significant processes (such as the importance of mixing) which are badly understood and their incorporation into phenomenological models should be a priority. The great importance of the structure of the slow ejecta to all models is abundantly clear and the increasing wealth of data relating to the envelopes of AGB and post-AGB stars is invaluable. It is clear that even at the simplest level, there can be no such thing as a single evolutionary path for all PNe. Ultimately the confrontation of models of specific objects with the observational data on them must be the way forward.

Myf Bryce, Franz Kahn and Alex Raga made helpful comments on the manuscript.

References

Arthur, S. J., Dyson, J. E. & Hartquist, T. W. (1992) Mon. Not. R. astr. Soc. (submitted).

Bachiller, R., Bujarrabal, V., Martín-Pintado, J., Planesas, R. & Gómez-Gonzalez, J. (1990) Astrophys. Space Sci. **171**, 195.

Balick, B. (1987) Astron. J. **94**, 671.

Balick, B., Gonzalez, G., Frank, A. & Jacoby, G. (1992) Astrophys. J. (in press).

Bond, H. & Livio, M. (1990) Astrophys. J. **355**, 568.

Borkowski, K. J., Sarazin, C. L. & Soker, N. (1990) Astrophys. J. **360**, 173.

Breitschwerdt, D. & Kahn, F. D. (1990) Mon. Not. R. astr. Soc. **244**, 521.

Burton, M. G. & Geballe, T. R. (1986) Mon. Not. R. astr. Soc. **223**, 13p.

Chu, Y.-H. (1989) In S. Torres-Peimbert (ed.), *Planetary Nebulae*, IAU Symposium 131, Kluwer Academic Publishers, Dordrecht, p.105.

Chu, Y.-H., Jacoby, G. H. & Arendt, R. (1987) Astrophys. J. Suppl. **64**, 529.

Dyson, J. E. (1992) Mon. Not. R. astr. Soc. **255**, 460.

Dyson, J. E. & Hartquist, T. W. (1992) Astro. Lett. & Comm. **28**, 301.

Dyson, J. E., Hartquist, T. W. & Biro, S. (1992) Mon. Not. R. astr. Soc. (submitted).

Dyson, J. E., Hartquist, T. W., Pettini, M. & Smith, L. J. (1989) Mon. Not. R. astr. Soc. **241**, 625.

Forveille, T. & Huggins, P. J. (1991) Astron. Astrophys. **248**, 599.

Frank, A., Balick, B. & Riley, J. (1990) Astron. J. **100**, 1903.

Ghanbari, J. (1989) Ph.D. Thesis, University of Manchester.

Hartquist, T. W. & Dyson, J. E. (1987) Mon. Not. R. astr. Soc. **228**, 957.

Hartquist, T. W. & Dyson, J. E. (1992) Quart. J. R. astr. Soc. (in press).

Hartquist, T. W., Dyson, J. E., Pettini, M. & Smith, L. J. (1986) Mon. Not. R. astr. Soc. **221**, 715.

Henney, W. J. & Dyson, J. E. (1992) Astron. Astrophys. (in press).

Huggins, P. J. (1992) In H. E. Schwarz (ed.), *Mass Loss on the AGB and Beyond*, Proc. 2nd ESO/CITO Workshop (in press).

Icke, V. (1991) Astron. Astrophys. **251**, 369.

Icke, V., Balick, B. & Frank, A. (1992) Astron. Astrophys. **253**, 224.

https://doi.org/10.1017/S0074180900171037 Published online by Cambridge University Press

Kahn, F. D. (1989) In S. Torres-Peimbert (ed.), *Planetary Nebulae*, IAU Symposium 131, Kluwer Academic Publishers, Dordrecht, p.411.

Kahn, F. D. & Breitschwerdt, D. (1990) Mon. Not. R. astr. Soc. **242**, 505.

Kahn, F. D. & West, K. A. (1985) Mon. Not. R. astr. Soc. **212**, 837.

Kwok, S., Purton, C. R. & Fitzgerald, P. M. (1978) Astrophys. J. **219**, L125.

Lutz, J. H., Kaler, J. B., Shaw, R. A., Schwarz, H. E. & Aspin, C. (1989) Publ. Astr. Soc. Pacific **101**, 966.

Meaburn, J., Hartquist, T. W. & Dyson, J. E. (1988) Mon. Not. R. astr. Soc. **230**, 243.

Meaburn, J., Nicholson, R., Bryce, M., Dyson, J. E. & Walsh, J. R. (1991) Mon. Not. R. astr. Soc. **252**, 535.

Meaburn, J., Walsh, J. R., Clegg, R. E. S., Walton, N. A., Taylor, D. & Berry, D. S. (1992) Mon. Not. R. astr. Soc. **255**, 177.

Mellema, G., Euderink, F. & Icke, V. (1991) Astron. Astrophys. **252**, 718.

Middlemass, D., Clegg, R. E. S., Walsh, J. R. & Harrington, J. P. (1990) In M. O. Mennessier & A. Omont (eds.), *From Miras to Planetary Nebulae: Which Path for Stellar Evolution?*, Editions Frontières, Gif-sur-Yvette, p.420.

Morris, M. (1987) Publ. Astr. Soc. Pacific **99**, 1115.

Olofsson, H. (1992) In H. E. Schwarz (ed.), *Mass Loss on the AGB and Beyond*, Proc. 2nd ESO/CITO Workshop (in press).

Pauldrach, A., Puls, J., Kudritzki, R. P., Méndez, R. H. & Heap, S. R. (1988) Astron. Astrophys. **207**, 123.

Plait, P. & Soker, N. (1990) Astron. J. **99**, 1883.

Schwarz, H. E. (1992) In H. E. Schwarz (ed.), *Mass Loss on the AGB and Beyond*, Proc. 2nd ESO/CITO Workshop (in press).

Schönberner, D. (1983) Astrophys. J. **272**, 708.

Smith, L. J., Pettini, M., Dyson, J. E. & Hartquist, T. W. (1984) Mon. Not. R. astr. Soc. **211**, 679.

Smith, L. J., Pettini, M., Dyson, J. E. & Hartquist, T. W. (1988) Mon. Not. R. astr. Soc. **234**, 625.

Soker, N. (1989) Astrophys. J. **340**, 927.

Soker, N. (1990) Astron. J. **99**, 1869.

Soker, N. (1992a) In H. E. Schwarz (ed.), *Mass Loss on the AGB and Beyond*, Proc. 2nd ESO/CITO Workshop (in press).

Soker, N. (1992b) Astrophys. J. (in press).

Soker, N., Borkowski, K. J. & Sarazin, C. L. (1991) Astron. J. **102**, 1381.

Soker, N. & Harpaz, A. (1992a) Astrophys. J. (in press).

Soker, N. & Harpaz, A. (1992b) (preprint).

Soker, N. & Livio, M. (1989) Astrophys. J. **339**, 268.

Soker, N., Zucker, D. B. & Balick, B. (1992) Astrophys. J. (submitted).

Wang, L.-F. (1992) (in preparation).

https://doi.org/10.1017/S0074180900171037 Published online by Cambridge University Press