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Abstracts of recently accepted papers

Radiation gasdynamics of planetary nebulae – VI. The evolution of aspherical planetary nebulae

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This paper reports the results of the numerical study of the formation of aspherical Planetary Nebulae through the Generalised Interacting Winds Model, taking into account the effects caused by the evolving central star and fast wind. The results show for the first time that aspherical nebulae do form within the required time scale. Consideration of the development of the nebula shows that in the early stages it is the ionization of the aspherical AGB wind that contributes considerably to the shaping of the nebula. Furthermore the passing through of the ionization front may modify the density distribution in the slow wind, leading to the formation of a surrounding envelope, and sometimes a different morphology for the nebula than was to be expected from the initial conditions. I consider how the different phases of ionization fronts and wind swept bubbles can be observationally distinguished.

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The Outflow Structure of NGC 6537

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We present high and low resolution spectroscopy and narrow-band imaging of the unusual bipolar outflow source NGC 6537. As a consequence, we are able for the first time to construct large scale velocity maps of this source; note the presence of strongly variable core outflow densities, rising to a peak value $n_e \sim 1.7\ 10^4\ cm^{-3}$; find evidence for substantial core ionization stratification; and demonstrate the presence of a spatially extended, intermediate velocity wind extending over a range $\Delta v_I \simeq 700\ km\ s^{-1}$, together with a more tightly constrained component having $\Delta v \simeq 4400\ km\ s^{-1}$. This latter wind appears co-spatial with the slower, higher intensity core emission, and may be responsible for driving denser clumps of material to a typical velocity $v_{exp} \sim 18\ km\ s^{-1}$.

Temperatures appear to vary significantly over the core, from a peak value $T_e \simeq 1.0\ 10^4\ K$ close to the the nucleus, to $\simeq 0.9\ 10^4\ K$ for projected radial offsets of $5''$, whilst extinction is more or less constant, yielding a mean estimate $A_v \simeq 3.4 \pm 0.2\ mag$.

Application of a shock outflow model suggests that most of these features are readily explained providing wind mass-loss rates are of order $\dot{M}_\star \sim 6\ 10^{-8}$–$6\ 10^{-7}\ \ M_\odot\ yr^{-1}$, and the flow is strongly collimated by an interior disk. In particular, we are able to provide excellent simulations for both the complex kinematics, and unusual bipolar.

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Polarization of Astronomical Maser Radiation. III. Arbitrary Zeeman Splitting and Anisotropic Pumping

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General solutions of the maser polarization problem are presented for arbitrary absorption coefficients. The results are used to calculate polarization for masers permeated by magnetic fields with arbitrary values of x_B, the ratio of Zeeman splitting to Doppler linewidth, and for anisotropic (m-dependent) pumping. In the case of magnetic fields, one solution describes the polarization for overlapping Zeeman components, $x_B < 1$. The $x_B \to 0$ limit of this solution reproduces the linear polarization derived in previous studies, which were always conducted at this unphysical limit. Terms of higher order in x_B have a negligible effect on the magnitude of q. However, these terms produce some major new results: (1) The solution is realized only when the Zeeman splitting is sufficiently large that $x_B > \sqrt{S_0/J_s}$, where S_0 is the source function and J_s is the saturation intensity (pumping schemes typically have $S_0/J_s \sim 10^{-5}$–10^{-8}). When this condition is met, the linear polarization requires $J/J_s \geq x_B$, where J is the angle-averaged intensity. This condition generally requires considerable amplification, but is met long before saturation ($J/J_s \geq 1$). (2) The linear polarization is accompanied by circular polarization, proportional to x_B. Because x_B is proportional to the transition wavelength, the circular polarization of SiO masers should decrease with rotation quantum number, as observed. In the absence of theory for $x_B < 1$, previous estimates of magnetic fields from detected maser circular polarization had to rely on conjectures in this case and generally need to be revised downward. The fields in SiO masers are $\sim$ 2–10 G and were overestimated by a factor of 8. The OH maser regions around supergiants have fields of $\sim$ 0.1–0.5 mG, which were overestimated by factors of 10–100. The fields were properly estimated for OH/IR masers ($\leq$ 0.1 mG) and H_2O masers in star-forming regions ($\sim$ 15–50 mG). (3) Spurious solutions that required stability analysis for their removal in all previous studies are never reproduced here; in particular, there are no stationary physical solutions for propagation at $\sin^2\theta < \frac{1}{3}$, where θ is the angle from the direction of the magnetic field, so such radiation is unpolarized. These spurious solutions can be identified as the $x_B = 0$ limits of non-physical solutions and they never arise at finite values of x_B, however small. (4) Allowed values of θ are limited by bounds that depend both on Zeeman splitting and frequency shift from line center. At $x_B \leq 10^{-3}$, the allowed phase space region encompasses essentially all frequencies and $\sin^2\theta > \frac{1}{3}$. As the field strength increases, the allowed angular region shrinks at a frequency-dependent rate, leading to contraction of the allowed spectral region. This can result in narrow maser features with linewidths smaller than the Doppler width and substantial circular polarization in sources with $x_B \geq 0.1$. When $x_B \geq 0.7$, all frequencies and directions are prohibited for the stationary solution and the radiation is unpolarized.

Another solution describes the polarization when the Zeeman components separate. This occurs at line center when $x_B > 1$ and at one Doppler width when $x_B > 2$. The solution is identical to that previously identified in the $x_B \to \infty$ limit, and applies to OH masers around HII regions. A significant new result involves the substantial differences between the π- and σ-components for most propagation directions, differences that persist into the saturated domain. Overall, HII/OH regions should display a preponderance of σ-components. The absence of any π-components in W3(OH) finds a simple explanation as maser action in a magnetic field aligned within $\sin^2\theta < \frac{2}{3}$ to the line of sight.

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SiO maser survey of the galactic bulge IRAS sources: IV. Observationnal properties of SiO masers

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Statistical properties of SiO masers are studied based on the observations of color selected IRAS sources in the direction of the Galactic bulge. Among 313 observed late-type stellar objects in the region of $|l| < 15°$ and $3° < |b| < 10°$, 193 were detected in the SiO v=1, J=1-0 line and/or the v=2, J=1-0 line. We discuss the relation between SiO detection rate and infrared properties for these sources. The sources are divided into bulge and disk members in terms of the luminosity distance. The SiO detection rate is found to be appreciably higher for the bulge sources than for the disk sources, and that the detection rate is higher for variable IRAS sources (with IRAS variability index above 90) than that for the nonvariable sources (with the index below 90). We also find that the center velocities of the v=1 and v=2, J=1-0 lines are almost equal to the average velocity of OH 1612 MHz double peaks. This implies that the SiO velocity is a good indicator of the stellar radial velocity, approving the analysis of bulge stellar kinematics using SiO radial velocities. On average, the line-intensity ratio of the v=1 to v=2 lines is approximately unity and there seems no systematic difference on the ratio between disk and bulge sources. The SiO line intensities are very weakly correlated with IRAS fluxes for the bulge sources. No clear correlation is found between the SiO line width and the stellar expansion velocity. This indicates that the SiO line width cannot be used as a measure of luminosity of the infrared sources.

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Modelling of the Dust and Gas Outflows from OH26.5+0.6 : The Superwind

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We have observed the extreme OH/IR star, OH26.5+0.6, in the infrared dust continuum and in the submillimeter rotational lines of CO. Mid-infrared images reveal the compact nature of the circumstellar shell ($< 0.5''$). A deep 9.7μm absorption feature and an absorption at 18μm show that the dust mass loss rate is very high. However, the low antenna temperatures of CO J=1-0 and 2-1 lines suggest that the outer part of the circumstellar shell is much more tenuous. In order to resolve this discrepancy, we have observed the J=3-2 and 4-3 CO rotational transitions.

We have developed a model for the circumstellar shell for OH26.5+0.6 which is consistent with the infrared and submillimeter observations. The dust and gas data are well fitted by a two-shell model, consisting of a dense shell surrounded by a more tenuous shell. The former, we identify with the superwind ($\dot{M} = 5.5 \times 10^{-4}$ $M_\odot$/yr) and the latter with mass loss on the AGB ($\dot{M} = 10^{-6}$ $M_\odot$/yr). The transition between the two mass loss phases is shown to be rather abrupt ($\Delta t < 150$ years). Depending on the mass of the progenitor, this superwind phase may be the last thermal pulse (for $M_* < 1.5$ $M_\odot$), or the first of a series of the superwind phases (for up to $8M_\odot$), punctuated by a period of low mass loss rates, before the star evolves off the AGB.

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Hubble Space Telescope Observations of Planetary Nebulae in the Magellanic Clouds IV: [O III] Images and Evolutionary Ages

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The Planetary Camera of the Hubble Space Telescope has been used to obtain images in the [O III] 5007 Å line for a sample of 15 planetary nebulae in the Magellanic Clouds selected to eliminate any selection bias in either excitation class or in flux (for $\log F(H\beta) > -13.7$ erg cm^{-2} s^{-1}). These images are used to derive the physical dimensions, the spatial structure and the kinematic ages of the nebulae. The raw images were deconvolved using the Richardson-Lucy Image Restoration Algorithm, and based on extensive tests of model images, a limit of 100 iterations of the algorithm was adopted. The restored images show clear evidence for size evolution across the H-R Diagram. The younger, low excitation, compact planetary nebulae tend to be systematically smaller than photoionisation models based on ground-based data would predict, suggesting these planetary nebulae have a central reservoir of dense atomic and molecular gas. This gas lies close to the central star and is undergoing ionisation and being accelerated into outflow. Planetary Nebulae previously classified as nitrogen-rich objects with massive central stars (Peimbert Type I), show the bipolar "butterfly" symmetry that is also a characteristic of their Galactic counterparts. The derived kinematic ages range from less than 1000 years up to almost 5000 years, but show little sign of systematic increase along the evolutionary tracks. The true ages of the larger objects are systematically underestimated because of acceleration of the nebular shell during its lifetime. Using both the empirical fit that we had previously derived for the expansion velocity as a function of the position on the H-R Diagram, and the theoretical evolutionary tracks of the central star, we have derived two semi-empirical estimates for the evolutionary timescales based upon the nebular size, and the measured dynamical age. If these evolutionary timescales are to be consistent with the evolutionary age derived from theory, then He-burners outnumber H-burners in the approximate ratio 2:1.

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The Formation of Barium and CH Stars and related objects

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We investigate the formation of barium (Ba) stars and CH stars via binary interactions. We consider four evolutionary channels for their formation: wind accretion, wind exposure, stable Roche lobe overflow (RLOF), and common-envelope (CE) ejection, and carry out Monte-Carlo simulations. We also explore the effects of model parameters, such as a tidal-enhancement parameter for stellar wind, a maximum stellar mass for s-processing, and a minimum core mass for thermal pulsation, on our results. We also explore the effects of various assumptions about age, mass-ratio distribution and wind velocity.

Our results show that binary interaction is successful in explaining the formation of Ba and CH stars. We successfully explain the distribution of orbital periods, the distribution of mass functions and the number of observed Ba stars. We also support the views (a) that a tidally enhanced stellar wind exists, (b) that thermal pulsation may begin at an earlier phase during the asymptotic giant branch (AGB) than is usually assumed, and (c) that the maximum stellar mass for s-processing is about $2\,M_{\odot}$. We also find that the degree of Ba pollution is strongly correlated with orbital period. The average mass of strong Ba stars is estimated to be $1.8\,M_{\odot}$, and of all Ba stars $1.7\,M_{\odot}$; the average mass for the white dwarf (WD) companions in the Ba-star binaries is estimated to be $0.60\,M_{\odot}$. The average mass of strong CH stars is estimated to be $1.2\,M_{\odot}$, and the average mass for their WD companions is estimated to be $0.62\,M_{\odot}$. The total number of Ba stars in the Galaxy brighter than 10th apparent magnitude is estimated to be 6000, while that of CH stars is much less.

We also investigate the formation of pre-Ba/CH stars, CVs, Algols, DDs and symbiotics. Some encouraging results are found, although much work needs to be done in order to understand fully their formation, especially of pre-Ba/CH stars and of symbiotics.

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