Planetary Nebulae

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1 PNe Formation

Low mass stars (less than 8 M⊙) will travel through the asymptotic giant branch (AGB) of the familiar HR-diagram. During this stage of evolution, energy generation is primarily relegated to a shell of helium just outside of the carbon-oxygen core. This thin shell of fusing He cannot expand against the outer layer of the star, and rapidly heats up while also quickly exhausting its reserves and transferring its head outwards. When the He is depleted, Hydrogen burning begins in a shell just a little farther out. Over time, helium builds up again, and very abruptly begins burning, leading to a shell-helium-flash (thermal pulse). During the thermal-pulse AGB phase, this process repeats itself, leading to mass loss at the extended outer envelope of the star. The pulsations extend the outer layers of the star, causing the temperature to drop below the condensation temperature for grain formation (Zijlstra 2006). Grains are driven off the star by radiation pressure, bringing gas with them through collisions.

The mass loss from pulsating AGB stars is oftentimes referred to as a wind. For AGB stars, the surface gravity of the star is quite low, and wind speeds of ~10 km/s are more than sufficient to drive off mass. At some point, a super wind develops that removes the envelope entirely, a phenomenon not yet fully understood (Bernard-Salas 2003). The central, primarily carbon-oxygen core is thus exposed. These cores can have temperatures in the hundreds of thousands of Kelvin, leading to a very strong ionizing source. The ejected material begins to ionize and a planetary nebula is formed. Eventually the core stops burning completely, and fades into a passive white dwarf while the ever-expanding shell of ejecta is mixed into the interstellar medium.

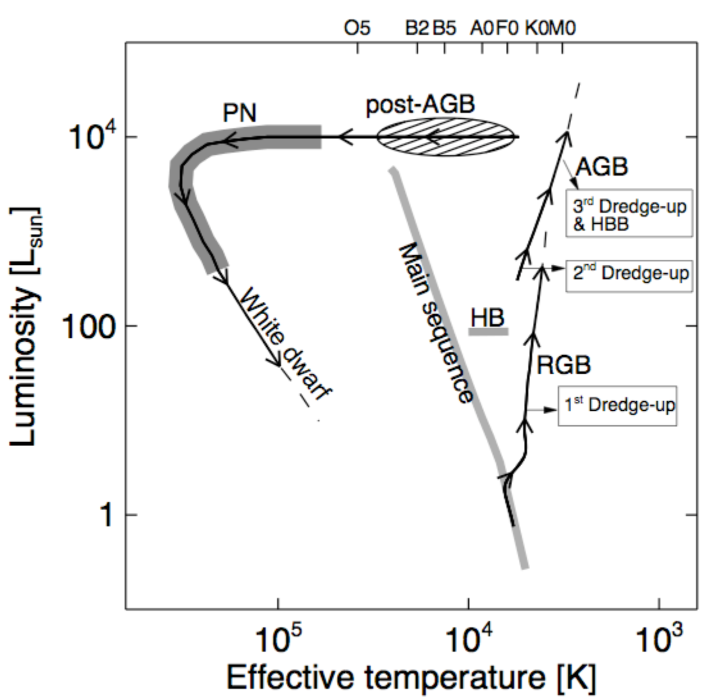

Figure 1
The transition of an AGB star through the planetary nebula phase towards the white dwarf region of the HR-diagram. Notice that effective temperature reaches well into the 10^5 K range during the PN phase.

2 Environment and Structure

The hot stars at the centers of planetary nebulae (PNe) will readily provide UV photons, but are not "extremely" luminous due to small radii. A typical planetary nebula spectrum will have very little continuum, producing much of its flux in various emission lines. However, as is always true in blackbodies, a tail to higher energies exists. Thus, very near the star, the density of high-energy photons will allow effective ionization of certain species that will not be ionized farther from the star (see figure 2). This leads to the concept of "stratification of radiation" (Gurzadyan 1997). This has important consequences for the inferred sizes of PNe since measurements using different emission lines will yield different results. The atoms with the lowest ionization potential (Hydrogen) will indicate the largest sizes, while the highest potential atoms will show the smallest sizes.

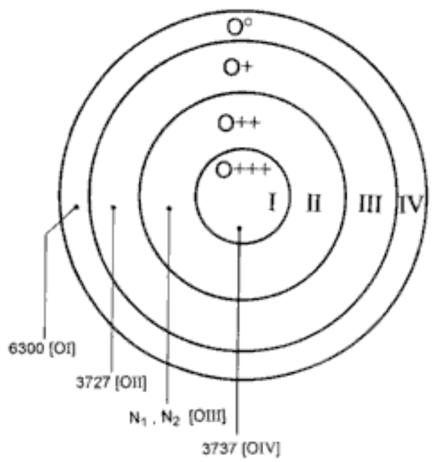

Figure 2
The stratification of radiation in a typical PNe will have high ionization potential species showing up near the core. Lower ionization states will be more prevalent farther from the star. This same effect applies to other multiply ionized atoms as well.

The stratification of radiation apparent in planetary nebulae means that seemingly innocuous conclusions may be over-simplifications. For instance, observations of PNe using narrow-band imaging centered on the [OIII] 4959,5007 lines will yield the conclusion that there is no emission from the core of the nebula. This is true for the [OIII] lines, but not true in an absolute sense. While a fast wind off the star can clear out material in the inner regions, it is likely that some highly ionized gas will remain. Spectroscopic observations in the optical will trace the expanding shell itself, where higher densities (of Oxygen for example) lead to increased emission. Thus, especially for Galactic nebulae, a double peaked emission line structure is evident due to the simultaneous observation of red and blue shifted lines in the expanding shell.

PNe are essentially miniature HII regions, with typical Stromgren radii on the order of 0.01 – 0.1 pc. However, there is a key difference to point out here, PNe are not embedded in thick regions of neutral gas, but are instead bounded by their own neutral material, ejected from their progenitor star. Furthermore, not every PNe has enough optical depth to fully attenuate the UV photon flux. A single PNe's properties will depend on how much material was lost from its host star, how long ago this mass was lost, whether this material is enriched with coolant (oxygen for instance), and can depend on the existence of magnetic fields and bipolar outflows.

One key observable difference between PNe and HII regions is the dearth of Hβ emission in PNe. The ratio of [OIII] 5007 to [OIII] 4959 to Hβ is roughly 10:3:1, while in HII regions, it ranges from 2:0.6:1 to 0.3:0.1:1 (Gurzadyan 1997). For a given flux in the [OIII] lines, Hβ emission is less in a PN than in an HII region. As is evident from the following equations, increasing temperature reduces the Hβ recombination coefficient and thus the observed Hβ flux. The central stars in PNe are ~10 times hotter than the stars in HII regions leading to reduced Hβ, and the increased dominance of [OIII] 4959,5007.

$$F_{H\beta} = \frac{1}{4\pi d^2}\left\{ h\upsilon_{H\beta} \int_0^{r=R_S} \alpha_{H\beta} n_e^2 4\pi r^2 dr \right\}$$

$$\alpha_{H\beta} h\upsilon_{H\beta} \approx 1.24 \times 10^{-25} (\frac{T}{10^4 K})^{-0.8795} \quad (\text{erg cm}^3/s)$$

Rosseland's theorem dictates that in low-density regions, short-wavelength radiation is transformed into long-wavelength radiation. In general, there are two competing processes going on. Consider the transitions 1-> 2 -> 3 -> 1 and 1 -> 3 -> 2 -> 1, in the second case, a single high-energy photon is transformed into two lower energy photons, while the first case is just the opposite. The dominance of one process over the other is dictated by the dilution of radiation from the star. In PNe, the dilution of radiation is ~ 10^{-13}. In this regime, the ratio $N_{1,2,3,1}/N_{1,3,2,1}$ ~ W = 10^{-13} (Gurzadyan 1997), meaning that the 1 -> 3 -> 2 -> 1 process will dominate entirely. This immediately explains a PNe observable, that the nebula emits much more energy in the optical than does the central star. This is because UV radiation is being processed into optical photons.

Consider the hydrogen component of a planetary nebula. The ionizing flux from the central star along with the low electron density will guarantee a very high ionization fraction. Most H atoms will be fully ionized or in the ground state. As shown above for Hβ, the flux of photons causing H transitions can be reduced drastically with high temperature. Thus, the nebular region can be optically thick to Lyman continuum photons, and completely opaque to Lyman series photons whose absorption coefficients are10^4 - 10^5 times that of the Lyman continuum (Gurzadyan 1997). Because of this, Balmer, Paschen, etc. series photons will escape the nebulae that is transparent at those wavelengths, while Lyα photons will be absorbed and reemitted repeatedly, eventually diffusing to the surface and escaping. This diffusing flux of Lyα photons may actually be important for dust heating (see section 5)

4 Abundance Discrepancies Between Methods

In planetary nebulae, abundances derived using O^{2+} in two different ways provides disparate results. Oxygen abundances measured through optical recombination lines (ORLs) (OII 4649) are systematically larger than abundances derived from collisionally excited lines (CELs) (OIII 5007) by factors surpassing 10 (up to 1,000). CEL emission is preferential in hot regions, while ORL emission is just the opposite (Peimbert 1967). Thus, CEL measurements would overestimate the temperature of the entire nebula, and thus underestimate the abundance (Wesson et al. 2005), making ORL abundances more accurate. However, this scenario cannot account for such large abundance discrepancies. A test of this scenario is to use IR fine-structure lines that have excitation temperatures (~1000 K) way below the typical temperature of the nebula, and thus are impartial to temperature fluctuations. Abundances derived from such lines do not match those from ORLs suggesting something else is going on.

Another explanation suggests that isolated hydrogen-deficient material within the nebula is causing the discrepancy. Within these regions, cooling is primarily through heavy element ion IR emission, and can bring the temperatures below 1000 K. ORL emission would be boosted while CEL emission would be severely reduced. Thus, in this model, CEL abundances trace the bulk of the nebular material, while ORL abundances merely reflect the H-deficient knots.

5 IR Emission in PNe

Planetary nebulae spectra show very little UV and optical continuum emission because the gas is too tenuous to emit blackbody radiation, and the central star is too small to have a large luminosity. However, in the infrared portion of the spectrum, a continuum becomes apparent near 10 microns, and peaks near 30 microns (fig 3), suggesting the existence of emitting material at 200 – 300 K. One logical explanation is the presence of dust, heated by Lyα or Lyman continuum photons. As mentioned earlier, nebulae are opaque to Lyα photons, and will thus slowly diffuse to the outer boundary and escape. Thus, Lyα photons should be available to interact with dust grains and provide thermal energy. If this were true, then within a volume V, the infrared luminosity would be proportional to the Lyα luminosity as shown below.

$$L_\alpha = n_e^2 \alpha_r h \upsilon_\alpha V$$
$$L_{IR} = q \times n_e^2 \alpha_r h \upsilon_\alpha V$$

Assuming a constant mean mass for all PNe makes $n_e V$ = constant. This suggests that the ratio of infrared luminosity to Lyman alpha luminosity is proportional to the electron density. However, this is not supported by observations (Gurzadyan 1997). One possible explanation is the existence of extra heating from high energy Lyman continuum photons (λ <~ 500 Angstroms).

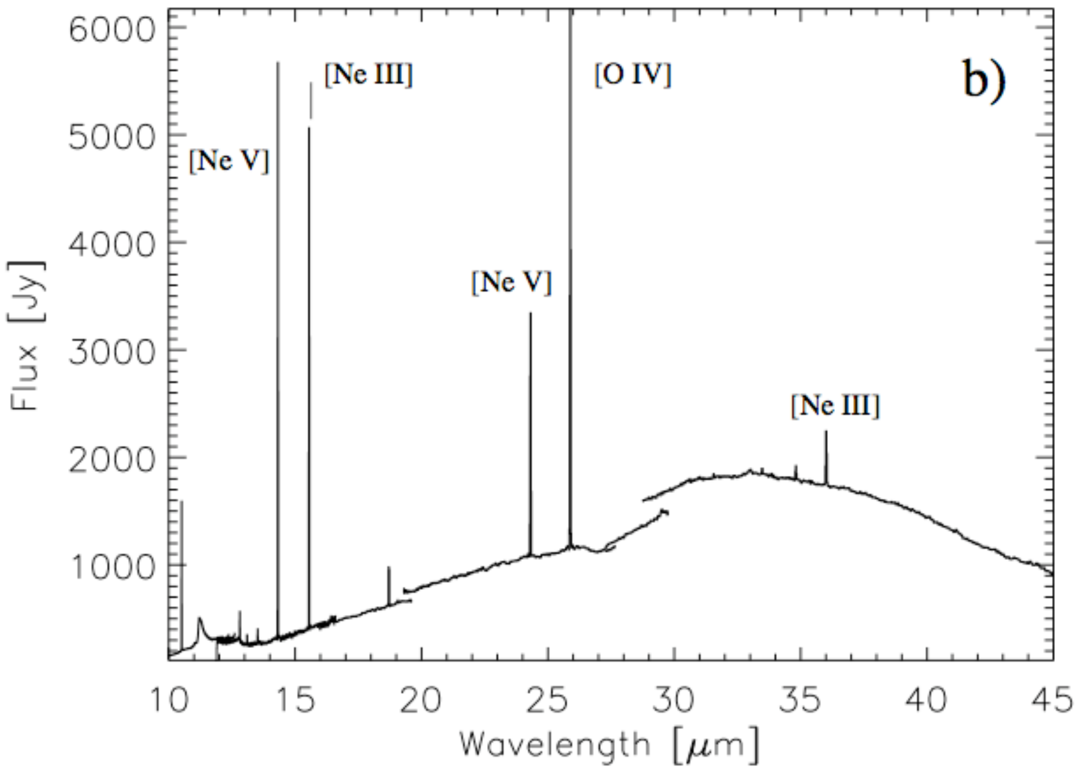

Figure 3: The infrared spectrum for a typical PNe will show several forbidden transitions on top of a continuum with peak near 30 μm (100 – 300 K). This blackbody distribution cannot be from cold gas, but could be from dust emission.

6 Summary

Planetary Nebulae are the end products of the AGB phase of low to midsize stars. The ejected material expands in a shell with a typical velocity of about 30 Km/s. The low-density nature of the nebula will cause the UV photons from the extremely hot central star to be processed into longer wavelength photons. In this way, the nebula can produce much more optical luminosity than the small central star because "invisible" UV photons are reduced to optical photons. The hot central star will also cause a stratification of radiation because higher ionization potential species (e.g. OIV) can only emit near the surface of the star, while lower potential species (OIII) will dominate further out.

Oxygen abundances measured via optical recombination lines (OII), and collisionally excited lines ([OIII]) do not agree. Small density and temperature inhomogeneities cannot account for this discrepancy. Enter the two-abundance model in which, besides a regular nebular component, there exists a small (1% of the nebula) contribution from cold H-deficient knots. In the absence of hydrogen, these regions can cool to a few hundred Kelvin via infrared fine structure and recombination lines.

Infrared continuum emission at 10 – 30 microns suggests a radiating component of dust, heated via a combination of Lyman alpha and hard Lyman continuum photons.

7 References

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