The X-ray Emission of Planetary Nebulae

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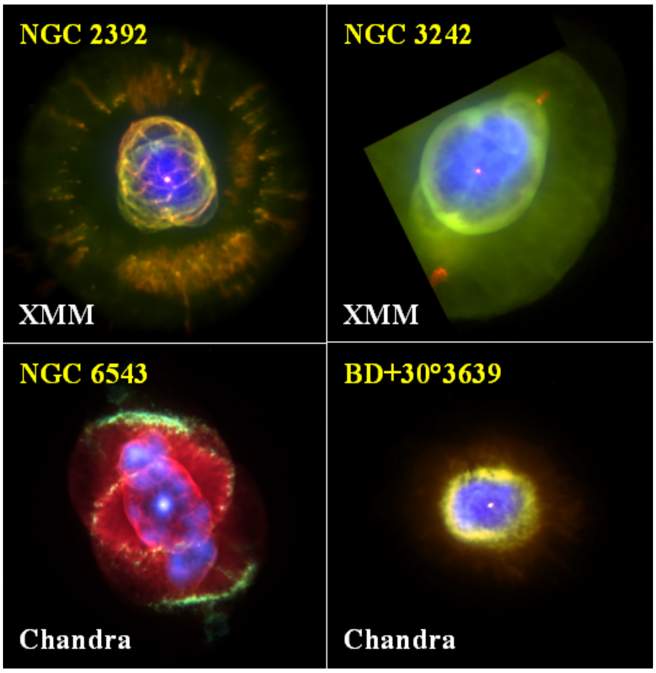
Planetarische Nebel sind ausgedehnte Gashüllen, die Sterne mittlerer Masse am Ende ihrer Entwicklung abstoßen und durch ihre ionisierende UV-Strahlung zum Leuchten anregen. Durch spektroskopische Untersuchungen ist seit langem bekannt, dass diese Nebel Temperaturen von typischerweise 10000 Kelvin und Dichten von einigen 1000 Teilchen pro Kubikzentimeter aufweisen. Mit Hilfe der Röntgensatelliten **Chandra** und **XMM-Newton** wurde nun entdeckt, dass viele Planetarische Nebel trotz ihrer relativ moderaten Temperaturen zweifelsfrei Quellen von Röntgenemission sind. Wie eine genauere Analyse der Beobachtungsdaten zeigt, stammt die Röntgenstrahlung aus dem zentralen Hohlraum des Planetarischen Nebels, wo Temperaturen von einigen Millionen Kelvin und Dichten von nur 10–100 Elektronen pro Kubikzentimeter vorherrschen müssen. Am **AIP** werden hydrodynamische Modellrechnungen durchgeführt, welche die auf den ersten Blick unerwarteten Röntgenbeobachtungen sogar quantitativ erklären können.



A sample of Planetary Nebulae observed with the X-ray space observatories XMM-*Newton* (ESA) and Chandra (NASA). The detected X-ray emission is shown in blue, superimposed on the optical Hubble Space Telescope images (red and green colors). Observations and image processing © **M. Guerrero et al. 2005.**

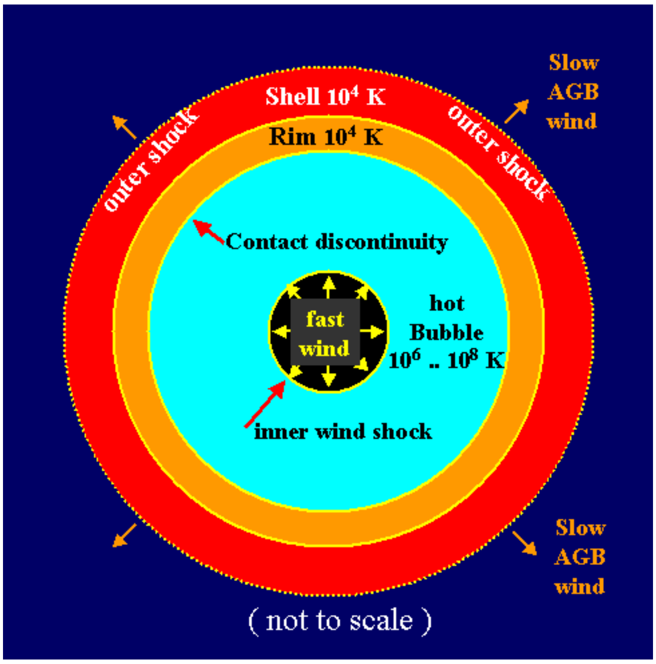
X-ray observations of Planetary Nebulae

Over the last years, the two large X-ray space observatories **XMM-*Newton*** (ESA) and **Chandra** (NASA) have been used to map the X-ray emission of several Planetary Nebulae (PNe) with high spatial and spectral resolution. These observations have shown without doubt that the X-ray emission does not originate from the central star but from the central cavity of the nebulae. As is evident from the sample of composite images shown below, the extended diffuse X-ray emission (blue) is confined to the inner parts of the nebulae. Closer inspection indicates that the emission is somewhat brighter towards the limb. The observed spectra reveal that most of the X-ray luminosity is due to emission lines of highly ionized elements, mostly oxygen (O VII), nitrogen (N VI), carbon (C V), and neon (Ne IX). From the strengths of theses emission lines and other spectral features, it is possible to determine the temperature and density of the emitting plasma quite accurately. For the shown sample PN, the resulting temperatures lie between 1.7 and 2.5 million K, the densities between 15 and 130 electrons per cm^3. These values are typical for all cases studied so far.

As explained in the following section, standard hydrodynamic models describing the formation and evolution of Planetary Nebulae clearly fail to predict the observed X-ray emission. However, we demonstrate below that improved hydrodynamic models taking into account thermal electron heat conduction can reproduce the observed X-ray properties of PNe surprisingly well.

Hydrodynamical Modeling

According to the generally accepted scenario, the basic processes responsible for the formation of a Planetary Nebula are *colliding winds* and *photoionization* by the hot central star's UV radiation field. The related hydrodynamical processes lead to a complex structure of distinct radial shells (see sketch below). The fast wind from the hot central star of several 1000 km/s is in free flow for only a short distance before being thermalized in the *inner shock*. At this point, roughly half of the wind's kinetic energy is converted into heat. The shocked gas constitutes the so called *'hot bubble'*. Depending on the wind power, the standard



Schematic physical structure of a Planetary Nebula. Only rim (orange) and shell (red) are visible in optical light.

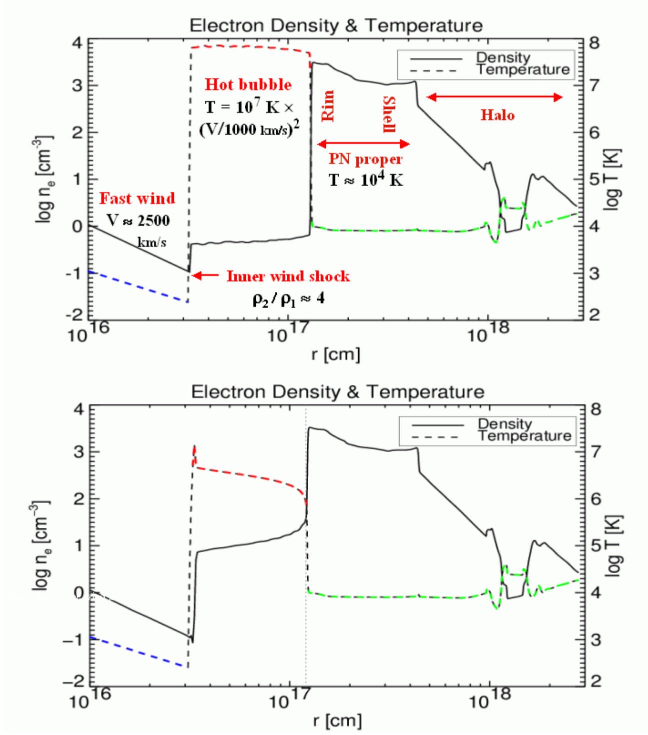
models predict resulting temperatures of the order 10^7 K to 10^8 K, and densities of about 1 electron per cm^3. Hence, the 'hot bubble' is found to be too hot and too tenuous to provide the observed X-ray emission.

However, the hot gas is surrounded by much cooler (10^4 K) nebular gas, and electron heat conduction across the narrow interface between hot and cool gas (*contact discontinuity*) becomes an important energy transport mechanism.

With is motivation, new hydrodynamic models including electron heat conduction have been computed at the AIP. It turned out that conductive heat losses efficiently reduce the temperature of the 'hot bubble', while at the same time evaporating the adjacent cool nebular gas. The physical conditions in the hot bubble are now very close to what has been inferred from the X-ray observations, as demonstrated in the next Figure.

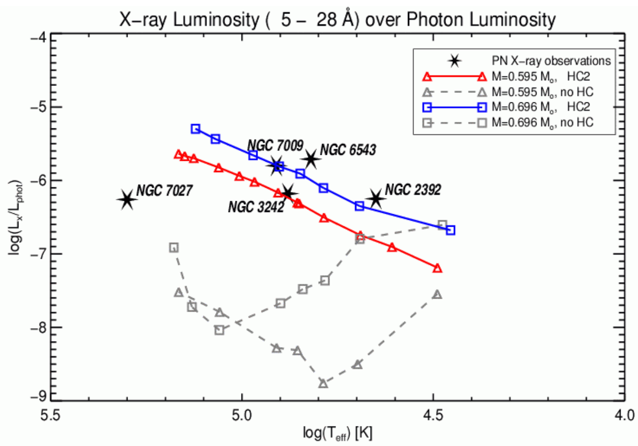
Observed and synthetic X-ray spectra

Based on the new PN models, we have computed detailed synthetic X-ray spectra using the software CHIANTI, a public IDL-package developed for the solar physics community. The agreement between observed and synthetic X-ray spectra is encouraging. Adding up the total X-ray emission between 0.5 and 2.5 keV (5-28 Å), gives the **X-ray luminosity** L_X, which can be compared with the L_X values derived from observations. As seen in the following Figure, the agreement between theory and observation is quite satisfactory,



Top: Radial dependence of temperature and electron density in the standard hydrodynamic PN model, with central star parameters T_{eff} ≈70000 K, L ≈ 5000 L⊙. **Bottom:** Same plot for a corresponding model with electron heat conduction. Note the much reduced temperature and increased electron density of the hot bubble.

provided the modeling includes heat conduction. Since magnetic fields efficiently suppress heat conduction, our results indicate that possible magnetic fields in the observed PNe must be very weak or have purely radial field lines.



Evolution of L_X/L^* as a function of T_{eff}, where L_X , L^*, and T_{eff} denote nebular X-ray luminosity (0.5-2.5 keV), stellar photon luminosity, and effective temperature, respectively. Observed values are indicated as black stars, while blue (M^*=0.7 M⊙) and red (M^*=0.6 M⊙) lines refer to the calculations with heat conduction, and gray lines to the corresponding results without heat conduction. Note that L_X/L^* is unaffected by the poorly know PN distances. Plotting the quantity L_X/L_W shows that less than 1% of the wind power L_W is lost as X-ray radiation.