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The formation of globules in planetary nebulae

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Abstract. We discuss the formation of globules in planetary nebulae, typified by those observed in the Helix Nebula. We show that the properties of the globules, their number, mass, separation, and overall geometry strongly support a scenario in which globules are formed by the fragmentation of a swept-up shell as opposed to models in which the knots form in the AGB wind. We show that the RT or other instabilities which lead to the break-up of shells formed in the nebulae by fast winds or ionization fronts can produce arrays of globules with the overall geometry and within the mass range observed. We also show that the presence of a magnetic field in the circumstellar gas may play an important role in controlling the fragmentation process. Using field strengths measured in the precursor AGB envelopes, we find that close to the central star where the fields are relatively strong, the wavelengths of unstable MRT modes are larger than the shell dimensions, and the fragmentation of the shell is suppressed. The wavelength of the most unstable MRT mode decreases with increasing distance from the star, and when it becomes comparable to the shell thickness, it can lead to the sudden, rapid break-up of an accelerating shell. For typical nebula parameters, the model results in numerous fragments with a mass scale and a separation scale similar to those observed. Our results provide a link between global models of PN shaping in which shells form via winds and ionization fronts, and the formation of small scale structures in the nebulae.

Keywords. Planetary nebulae: general, stars: mass loss, instabilities, magnetic fields

1. Introduction

Globules are the most striking small-scale structures seen in planetary nebulae (PNe). They consist of dense molecular condensations embedded in and around the periphery of the ionized gas (e.g., Huggins *et al.* 2002). In optical images their photo-ionized surfaces are seen in Hα and other lines, illuminated by the radiation of the central star. They often have cometary tails extending away from the star in the radial direction. Because of their small size, globules are only resolved at high resolution in nearby PNe, e.g., in NGC 7293 (the Helix Nebula) and NGC 6720 (the Ring Nebula), but they are expected to be a common feature of evolved PNe with a significant component of molecular gas.

The large number and the similarity of the globules in a PN like NGC 7293 point to an underlying formation mechanism with rather specific characteristics. In this paper we review the properties of globules, we ask whether simple models can explain some of their general characteristics, and we explore the possible role of magnetic fields in the globule formation process.

Table 1. Properties of the Globules in NGC 7293

globule mass	m_g	10^{-5} $M_\odot$	Huggins *et al.* (2002)
shell mass	M_s	0.2 $M_\odot$	Young *et al.* (1999)
number of globules	N	20,000	Meixner *et al.* (2005)
distance from star	r	6–15$\times10^{17}$ cm	
angular spacing	θ	0.02 rd	This paper
shell width/radius	$\Delta r/r$	1/20	Forveille & Huggins (1991)

2. Properties of the globules

Table 1 lists the measured properties of globules in NGC 7293 that are likely relevant to the formation process. The evolution of mature globules is dominated by photo-ionization processes, but we are interested here in the mechanisms that determine quantities such as the number and mass-scale of fragments from which the mature globules form.

Most of the properties listed in Table 1 are self-explanatory. The typical angular spacing of the globules (relative to the central star) is an especially useful quantity because it does not vary with expansion or the evolution of the globules: it is estimated here from the surface density in the main ring given by Meixner *et al.* (2005). The general distribution of the molecular gas seen in spatio-kinematic CO maps consists of partial shells; the ratio $\Delta r/r$ in the table is taken from high velocity resolution observations made at the systemic velocity. The spatio-kinematics of the low excitation ionized gas (e.g., Meaburn *et al.* 2005) support the shell picture.

NGC 6720 shares some of the characteristics of NGC 7293 but is a factor ~ 5 younger. Less of the neutral envelope is in globules, and they are at an earlier stage of development. Their morphology and relation to the nebula shell structure are of special interest, and are illustrated in Fig. 1.

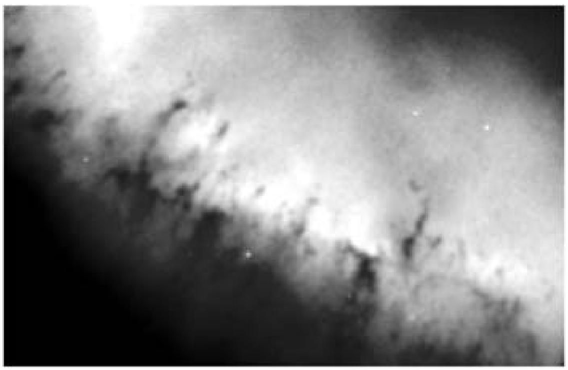

Figure 1. Section of NGC 6720 in the [O III] 5007Å line. The globules and shell are seen in absorption by dust against the nebula emission. The field is 23″ × 15″. HST WFPC2 data.

3. Shell models

3.1. *General characteristics*

The thin, shell-like distribution of the densest gas in NGC 7293 (and NGC 6720) provides strong support for a model of globule formation based on the fragmentation of a swept-up shell. For the break-up of a shell of radius R_s into fragments of size ΔR_s, equal to the shell thickness, we expect: $M_s \sim N m_g$, $N \sim 4\pi/\theta^2$, and $\theta \sim \Delta R_s/R_s$. These relations are approximately satisfied by the independently measured quantities given in Table 1.

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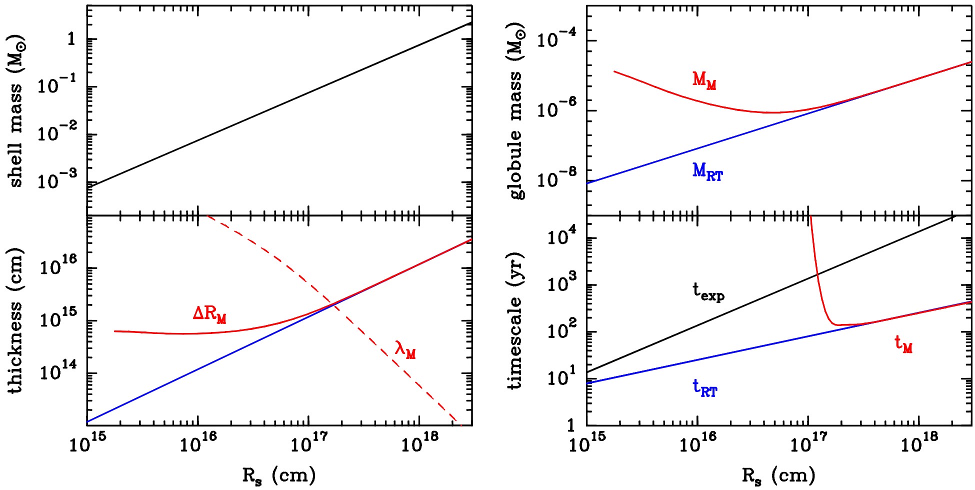

Figure 2. Evolution of shell properties as a function of shell radius (R_s). *Top left*: shell mass, *bottom left*: shell thickness, *top right*: fragment mass, *bottom right*: timescales. The subscript RT is for the classic RT case, and the subscript M is for the magnetic case. The curve λ_M (bottom left) shows the wavelength of the fast growing magnetic mode. See text for details.

In order to construct a physical model, we consider for simplicity the case of a shell driven by a constant, momentum-conserving wind (Kahn & Breitschwerdt 1990) which sweeps up the precursor AGB envelope with an r^{-2} density distribution. This simple case leads to a shell model that travels with a constant velocity. In reality, fragmentation of the shell will require modest accelerations. The difference between the two cases, in terms of shell conditions, will likely be small. The constant velocity shell is completely specified by the AGB wind velocity (U) and mass-loss rate ($\dot{M}$), the shell velocity (V_s), and the sound speed in the shell (c_s). Fig. 1 shows the properties of this shell as a function of the shell radius for $U = 15$ km s^{-1}, $\dot{M} = 10^{-4}$ $M_\odot$ yr^{-1}, $V = 23.5$ km s^{-1}, and $c_s = 1.5$ km s^{-1} (we assume the gas is in a PDR). The left hand panels show the shell mass, and thickness. Note that $\Delta R_s/R_s \sim 1/100$ is close to that observed. Note also that M_s does not reach a few tenths of a solar mass until the shell is large $\sim 10^{17}$ cm. The top right panel shows the mass of fragments if the shell breaks up at radius R_s on a size scale ΔR_s. Note that the mass of a fragment is small at small R_s, and only reaches $> 10^{-6}$ $M_\odot$ at $R_s > 10^{17}$ cm.

3.2. *Fragmentation*

Several different processes have been suggested for the actual break-up of PN shells including the NTSI, the TSI and the related ISFI, and the RT instability (e.g., Dwarkadas & Balick 1998, Garcia-Segura *et al.* 1999). In simulations, the NTSI may develop at an early phase but it may not lead to fragmentation, and from the discussion above it is doubtful that it could generate the ensemble of observed globules at that time. The RT instability is well-studied and it occurs when the shell is accelerated. The onset of ionization is one of several means of shell acceleration and the RT instability may couple to the ISFI at that stage. Note also that propagation of the shell down a steeper than $\rho \sim r^{-2}$ gradient will also produce an acceleration. For a nominal acceleration of 10 km s^{-1}/1000 yr, the RT growth time for the length scale equal to ΔR_s is shown in the bottom left panel. It is significantly less than the expansion time of the shell for all values of R_s. Thus the shell is fragile. If it accelerates near this nominal level before it reaches 10^{17} cm, it will break-up into low-mass fragments with a low total mass.

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4. Effect of a magnetic field

The role of magnetic fields in PN formation is an area of ongoing debate. Significant fields are measured in the envelopes of AGB stars in the SiO, H_2O, and OH maser lines, and it can be expected that the fields will be swept up into PN shells. We explore here how this may affect the fragmentation process.

The presence of a tangential magnetic field at an interface (the situation expected in a swept-up shell) typically has a stabilizing effect. The theory is well studied for the RT instability, and simulations for the magnetic case have been reported by Jun *et al.* (1995). The field has two effects. First, it suppresses all RT modes at short wavelengths with a cut-off given by $\lambda_c = B^2/a\rho$, where a is the acceleration and ρ is the density of the shell (assumed to be much denser than the driving wind). Second, the wavelength of the fastest growing mode is $2\lambda_c$, with a growth rate similar to the non-magnetic case.

For the shell model discussed earlier, the curves with subscript M in Fig 2. show the effects of a magnetic field in the AGB wind. The field is assumed to have the form $B = (r/10^{16})^2$ mG, based on an ensemble of circumstellar envelopes (Vlemmings *et al.* 2002). At early times, the field contributes to the pressure when it is swept into the shell, with the result that the shell thickness increases, and the potential break-up mass for small R_s is 10^{-6}–10^{-5} $M_\odot$, close to that observed. The break-up can not, however, occur at these scales because at small R_s the magnetic-RT critical wavelength is much larger than the shell thickness. The break-up of the shell is suppressed in the early phases.

At larger R_s, where the fields become weaker, the critical wavelength decreases. and when it becomes comparable to the shell thickness, the growth time for the instability drops rapidly to a low value. The effect is like a switch. If the system is accelerating, it leads to the sudden, rapid break-up of the shell. At these scales the mass of the fragments and the total mass are in the observed ranges.

5. Conclusions

The properties of globules in PNe support a scenario in which globules are formed by fragmentation of a swept-up shell. Instabilities in simple shell models can produce arrays of globules with the overall geometry and within the mass range observed. The magnetic field in the AGB wind may play a key role in controlling the fragmentation process. Our results provide a link between global models of PN shaping and globule formation.

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