Massive Stellar Clusters
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Planetary Nebulae in Clusters

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Abstract. The number of planetary nebulae expected to be present in a massive (10^6 M$_\odot$) cluster is shown to be of the order of 1 nebula per cluster of 2 Gyr age, of which a fraction (10 percent or less) might be detectable. This number is larger for younger clusters, in which one should find planetaries of Type I (rich in He and N). Thus, massive stellar clusters of different ages could aid to establish a reliable empirical relation between nebular chemical composition and the mass of the progenitor star

1. Nebulae in Galactic clusters

At first sight, planetary nebulae may seem to be a rare species among globular clusters: of the about 160 clusters known in the Milky Way, only four are found to contain a nebula: M 15 (Pease 1928, Adams et al. 1984, Howard et al. 1997), M 22 (Gillett et al. 1988, Borkovski & Harrington 1991), Pal 6 and NGC 6441 (Jacoby et al. 1997). However, this small number of detections is entirely consistent with expectations from stellar evolutionary theory and the detection limits of the surveys undertaken in the Galaxy (Phillips 1979). Jacoby & Fullton (1994) estimated from extragalactic surveys a rather higher rate of 12 planetaries for the Milky Way's globular clusters. In the LMC, Webster (1976) identified one nebula in a red globular cluster.

Open cluster are less massive and thus offer a lower detection chance. In our Galaxy, NGC 2818 (age 0.7 Gyrs, turn-off mass 2.1 M$_\odot$) has a planetary (Tifft, Conolly, & Webb 1972, Dufour 1984) which is of Peimbert's (1978) Type I. In the field of NGC 6087 Koester & Reimers (1989) discovered what turned out to be a background nebula; in NGC 3572 Phelps & Janes (1991) spotted a ring nebula.

While such a small number might seem somewhat discouraging, let us estimate how many nebulae could be expected in a *massive* stellar cluster of any age.

2. How many planetaries are in a cluster?

Since planetary nebulae have a lifetime $\tau_{\rm PN}$ of a few 10 000 years, much shorter than the timescale for starformation in galaxies, the number of objects visible at the present time is given by the stellar death rate. Suppose a stellar population of total mass M having been formed by a single short interval of starformation. At an age a stars of the turn-off mass $m_{\rm TO}(a)$ are dying which will form young, compact planetary nebulae, while the nebulae ejected by stars slightly more massive with $m = m_{\rm TO}(a-\tau_{\rm PN})$ will cease to be observable. Thus the number of planetaries at the present time is

$$n_{\rm PN} = M \cdot \int_{m_{\rm TO}(a)}^{m_{\rm TO}(a-\tau_{\rm PN})} \frac{\Phi(m)}{m}\, dm \tag{1}$$

with the IMF Φ in units of mass per mass interval (Salpeter's IMF would be $\propto m^{-1.35}$). Because of the smallness of $\tau_{\rm PN}$ the integral is well approximated by

$$\begin{aligned} n_{\rm PN} &\approx M\, \frac{\Phi(m_{\rm TO}(a))}{m_{\rm TO}(a)}\, \left(m_{\rm TO}(a-\tau_{\rm PN}) - m_{\rm TO}(a)\right) \\ &\approx M\, \frac{\Phi(m_{\rm TO}(a))}{m_{\rm TO}(a)}\, \left|\frac{d\tau}{dm}\right|^{-1} \tau_{\rm PN} \end{aligned} \tag{2}$$

which involves the derivative of the relation of stellar lifetime and mass. We fit a differentiable relation to the results of the calculations of Maeder & Meynet (1989) for solar composition stars:

$$\tau(m) = \begin{cases} 0.0151 + 10.3/m^3 & \text{for } m \le 9\ {\rm M}_\odot \\ 0.0027 + 0.89/m^{1.6} & \text{for } m \ge 9\ {\rm M}_\odot \end{cases} \tag{3}$$

in Gyrs and $\rm M_\odot$, which gives a derivative of

$$\left|\frac{d\tau}{dm}\right| = 30.9/m^4 \tag{4}$$

in the region $m \le 9\,\rm M_\odot$.

Let us use – for simplicity – a power-law IMF with an exponent x between stellar masses $m_{\rm low}$ and $m_{\rm high}$

$$\Phi(m) = \frac{1+x}{m_{\rm high}^{1+x} - m_{\rm low}^{1+x}}\, m^{-x} \tag{5}$$

Putting things together, for a Salpeter IMF between 0.08 and 60 $\rm M_\odot$ ($\Phi(m) = m^{-1.35} / 6.23\,\rm M_\odot$), the number of planetary nebulae present in a stellar population of mass M and age a is

$$n_{\rm PN} = 0.0052\ M\ \tau_{\rm PN}\ m^{1.65} \tag{6}$$

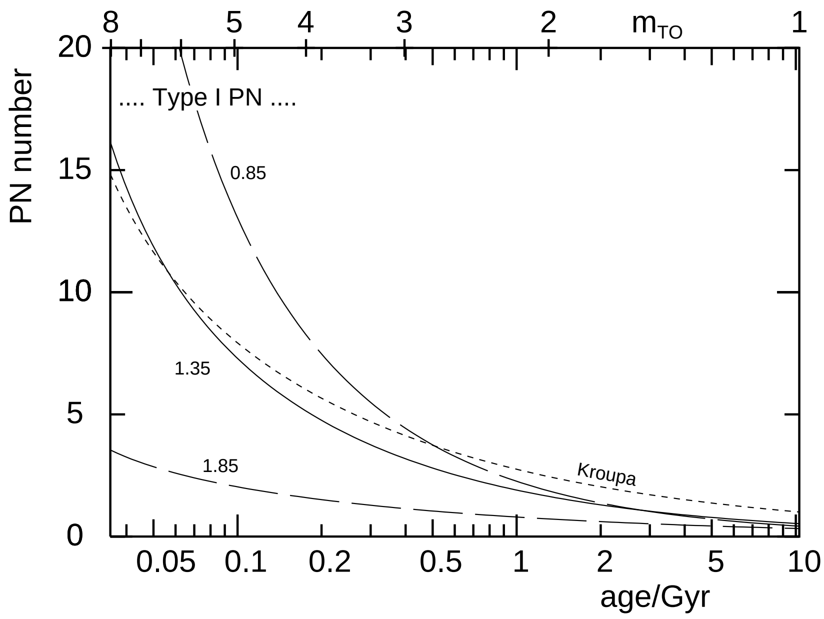

Figure 1. The number of planetary nebulae expected in a single age stellar population of 10^6 $M_\odot$ total mass, assuming a nebula lifetime of 100 000 yrs, for several IMFs

where τ_{PN} is in Gyrs. Or we can express it directly in terms of the age:

$$n_{PN} = 0.0052\, M\, \tau_{PN} \left(\frac{a - 0.0151}{10.3}\right)^{-0.55} \tag{7}$$

We note that this number scales directly with cluster mass and nebula lifetime, and that it *increases monotonically* towards lower ages.

Assuming a nebula lifetime of 100 000 yrs, we show in Fig. 1 the number of planetaries present in star clusters of 10^6 $M_\odot$ as a function of age, with power-law IMFs of the same mass limits but various slopes as well as Kroupa's (1995) IMF for the solar neighbourhood. One notes that the number of planetaries in young clusters is substantially greater than in old ones: at an age of 40 million years (turn-off mass of 8 $M_\odot$) one would expect ten times as many nebulae as in a cluster of the same mass but with an age of several Gyrs. It is worth emphasizing that this trend exists because the derivative of the lifetime–mass relation (here: 4) is always steeper than the IMF (here 0.85...1.85). The difference between Kroupa's and Salpeter's IMF is quite small, though Kroupa's IMF gives twice as many nebulae in old clusters. Changing the slope of a power-law IMF by 0.5 alters the nebula number merely by about a factor of two.

In Fig. 2 we show the extension of these curves towards higher turn-off masses, depicting the number of remnants from Type II supernovae. For simpler comparison, we kept the same lifetime of 100 000 years for the remnants.

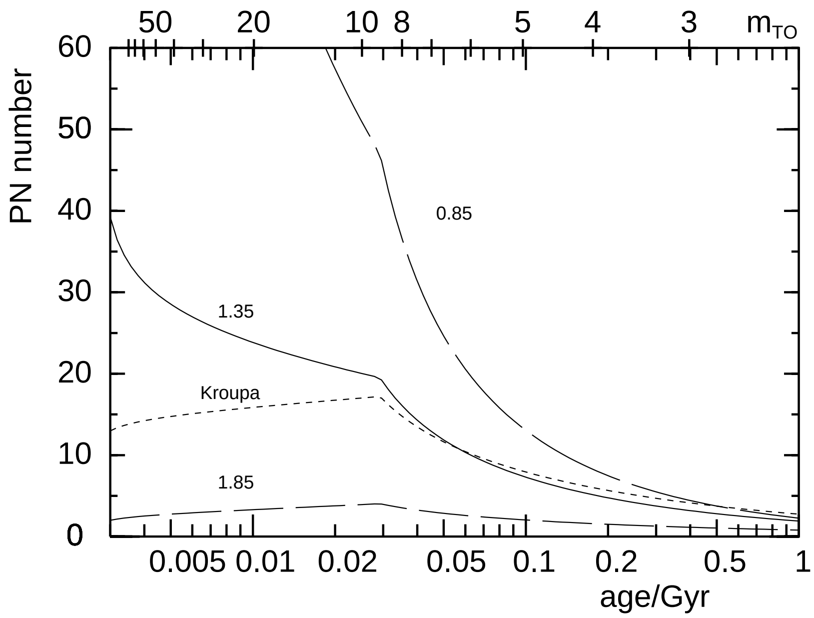

Figure 2. The number of stellar remnants (PN or SNR) expected in a single age stellar population of 10^6 $M_\odot$ total mass, assuming a remnant lifetime of 100 000 yrs, for several IMFs

SNRs would have lifetimes different from planetary nebulae, and detecting them in their various phases would also involve a different approach than the one suitable for planetaries. One notices that because the lifetimes for high-mass stars are much less sensitive to stellar mass (cf. Eqn. 3), the number of remnants may decrease with increasing mass, if the IMF slope is sufficiently steep. The somewhat prominent 'knee' at 9 $M_\odot$ is merely caused by our choice for the formula fitting the lifetimes, but the different slopes in the two mass regimes are not affected by splicing the fit formula in another way.

3. Discussion

The curves depict the number of existing nebulae only, and thus are not intended to give the number of detectable planetaries. Since the more massive central stars evolve more rapidly, the phase of the nebula being visible by its ionization is expected to be shorter. As a generally acceptable recipe for this is not straightforward to be had, we shall not make predictions for detection rates. Moreover, such a calculation would also entail the specifications of the instrumental setup and procedures.

However, we can use the experience from the Milky Way to get a rough estimate: in globular clusters (having a mass of say $3\,10^5$ $M_\odot$) we know about 0.03 nebulae per cluster. In order to match this figure with our results of 1 nebula per 10^6 $M_\odot$ – cluster at 10 Gyrs age, we need to assume a nebula lifetime of about 10 000 yr, i.e. 10 percent of what we had generously assumed before.

With this estimate for the detection limit, we should expect for 10^6 $M_\odot$ clusters: from 1 nebula per young cluster (50 Myr) down to 0.1 nebulae in old clusters (1 Gyr and older). Even though this estimate does not take into account properly the improvements in techniques and sensitivity available today, it does emphasize that looking for planetary nebulae in massive star clusters would be a realistic effort.

What are the perspectives? Planetary nebulae from the more massive progenitors, say above 4 $M_\odot$, are expected to show enrichment in helium, carbon, and nitrogen from production during the RGB and AGB phases. Nebulae of this kind (Peimbert's (1978) Type I nebulae) are indeed well known from the Galactic population. Their distribution in the Milky Way does support the notion that they must have come from stars more massive than the other types of nebulae, but no clear and firm empirical relation could be derived. On the other hand, calculations of the complex evolution of intermediate mass stars cannot yet provide sufficiently reliable predictions: Strong production of nitrogen due to the 3^{rd} dredge-up is expected from stars with masses above 4 $M_\odot$ (solar composition) or 3 $M_\odot$ (low metallicity) (Renzini & Voli (1981), van den Hoek & Groenewegen (1997)). With a more realistic prescription for the overshoot, Herwig et al. (1997) find that the 3^{rd} dredge-up occurs already in a 3 $M_\odot$ solar composition star.

Thus, a search for planetary nebulae in massive star clusters, and the subsequent analysis of their spectra taken with reasonably high quality could help to answer these topics:

- what is the upper limit for the progenitor stars of planetaries?
- where is the borderline between Type I and non-Type I objects?
- direct calibration to the relation of He– and N–overabundance with age and progenitor mass. Such a relation – if it exists – could be very useful for deriving the progenitor mass from nebular chemical properties
- determination of the nebular He and CNO abundances could serve as a test for theoretical models for the nucleosynthesis in intermediate mass stars. This point would be an essential aid in understanding the chemical evolution of galaxies

Hitherto, the first three topics can only be indirectly addressed in the Milky Way and the Magellanic Clouds by studies of the stars that most probably are just preceeding the nebular phase: AGB stars, Miras, OH/IR-stars. Massive stellar clusters, with their potential of being a stellar population of a definite age, might help to answer these questions directly for the planetary nebulae.

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