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SPECTROSCOPY OF BRIGHT EXTRAGALACTIC PLANETARY NEBULAE

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ABSTRACT

The spectroscopic properties of bright extragalactic planetary nebulae are reviewed, considering primarily their chemical abundances and their internal kinematics. Low-resolution spectroscopy is used to investigate how the precursor stars of bright planetary nebulae modify their original composition through nucleosynthesis and dredge up. At present, the evidence indicates that oxygen and neon abundances usually remain unchanged, helium abundances are typically enhanced by less than 50%, while nitrogen enhancements span a very wide range. Interpreting these changes in terms of the masses of their progenitor stars implies that the progenitor stars typically have masses or order $1.5\,M_{\odot}$ or less, though no models satisfactorily explain the nitrogen enrichment. High-resolution spectroscopy is used to study the internal kinematics of bright planetary nebulae in Local Group galaxies. At first sight, the expansion velocities are remarkably uniform, with a typical expansion velocity of 18 km/s and a range of 8-28 km/s, independent of the progenitor stellar population. Upon closer examination, bright planetary nebulae in the bulge of M31 expand slightly faster than their counterparts in M31's disk, a result that may extend generally to the planetary nebulae arising from old and young stellar populations. There are no very strong correlations between expansion velocity and global nebular properties, except that there are no large expansion velocities at the highest Hβ luminosities (i.e., the youngest objects never expand rapidly). These results independently suggest that bright planetary nebulae arise from a similar mass range in all galaxies. Nonetheless, there are good reasons to believe that bright planetary nebulae do not arise from identical progenitor stars in all galaxies.

Key words : planetary nebulae: chemical abundances, expansion velocities, evolution

I. INTRODUCTION

Over the past two decades, bright extragalactic planetary nebulae have served as interesting tools to study several issues relating to their host galaxies. First among these issues has been the use of the planetary nebula luminosity function (PNLF) as a distance indicator, e.g., Ciardullo et al. (1989, 2002). The constancy of the peak luminosity suggests that it is either degenerate to a variety of stellar evolution parameters, or that some subset of planetary nebulae populations are common to the majority of galaxies. Next, bright planetary nebulae are excellent probes of the stellar kinematics of their host galaxies, e.g., Romanowsky (2006). In clusters of galaxies, bright planetary nebulae have been found free, their progenitor stars having been stripped from their original host galaxies (e.g., Theuns & Warren 1997). These objects may be used to estimate the fraction of baryonic mass in galaxy clusters (Feldmeier 2006) or to study whether the galaxy cluster itself is dynamically-relaxed (Arnaboldi et al. 2004, Gerhard et al. 2007). Finally, bright planetary nebulae may be used to study the chemical evolution of their host galaxies, e.g., Richer et al. (1998). The chief advantage of using planetary nebulae rather than stars for studying the chemical evolution of their host galaxies is that it is easy (actually easiest) to study the abundances of light α-elements (composed of multiple helium nuclei) whose production in type II supernovae is believed to be well-understood (e.g., Clayton 2003).

In principle, the details of how planetary nebulae evolve need not be known for any of the foregoing. In practice, however, knowing how a probe works allows one to maximize the information available from its use. This is particularly relevant for understanding the PNLF as a distance indicator or using planetary nebulae to study the chemical evolution of their host galaxies. The main objection to the wider use of bright planetary nebulae for either of these purposes is that, quantitatively, the evolution of planetary nebulae is not well-known. From the viewpoints of both the nucleosynthesis resulting from the evolution of the stellar progenitors of planetary nebulae (e.g., Marigo 2001, Karakas & Lattanzio 2007) and the evolution of the central star and nebular shell (Jacoby 1989, Richer et al. 1997, Stanghellini & Renzini 2000, Marigo et al. 2004, Schönberner et al. 2007), there are significant uncertainties.

Here, results from the spectroscopy of the brightest planetary nebulae are used to address or restrict some of the above uncertainties. Note that planetary nebulae are expected to be the penultimate evolutionary phase of all single stars (and perhaps some binaries) span-

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ning the $0.8 - 8.0\,M_\odot$ range. In what follows, "bright planetary nebulae" are understood to be those within about 2.5 mag of the peak luminosity of the PNLF (in the light of [O III]λ5007). Given the discussion in the previous paragraph, all of the selection effects inherent in a luminosity-limited selection are obviously not clear, but it is believed that such a selection will favour planetary nebulae early in their evolution and, at low metallicity, the most oxygen-rich objects in each galaxy (previous references, also: Dopita et al. 1992, Richer & McCall 1995, Stasińska et al. 1998). Also, for the purposes of characterizing the age of the stellar populations from which planetary nebulae arise, stellar populations will be divided into "old" and "young". Stellar populations where star formation continues today are deemed young (disks of spiral galaxies, dwarf irregulars) while stellar populations where star formation has ceased are deemed old (ellipticals, dwarf spheroidals, bulges of spirals). Though crude, this division is sufficient for the needs of the present analysis.

II. CHEMICAL ABUNDANCES

Richer & McCall (2007, 2008) provide recent summaries of the chemical abundances in bright extragalactic planetary nebulae. Briefly, they find that oxygen and neon abundances usually remain unchanged throughout the evolution of the progenitor stars of bright planetary nebulae, helium is typically enriched by less than 50%, but that nitrogen enrichment varies over a wide range, from none at all up to factors exceeding forty times the initial nitrogen abundance. These results hold regardless of whether bright planetary nebulae arise in young or old stellar populations. Finally, the oxygen abundances observed in bright planetary nebulae reflect the chemical composition of their progenitor stellar populations.

These results may be understood if bright planetary nebulae arise from stellar progenitors that have all undergone similar nucleosynthetic and dredge-up evolution. If so, the initial masses of these stellar progenitors were typically less than $1.5\,M_\odot$ given the helium enrichment, though this should vary slightly due to the progenitors in different galaxies having different metallicities. Higher masses are unlikely, unless convective overshooting is inefficient. Otherwise, significant oxygen enrichment is expected, but is only rarely observed.

The nitrogen abundances are problematic for current theoretical models. Observations indicate a wide range in nitrogen abundance at a given oxygen abundance. In principle, nitrogen enrichment is a function of stellar mass. The highest nitrogen enrichment observed implies masses sufficiently high that hot bottom burning occurs, i.e., carbon is converted to nitrogen at the bottom of the convective envelope of the progenitor while on the asymptotic giant branch (AGB), implying masses above about $3\,M_\odot$. Progenitor stars of these masses should be absent in galaxies where most star formation stopped several Gyr ago. Furthermore, in addition to strong nitrogen enrichment, these stars should strongly enrich helium, and no case of simultaneous strong enrichment in helium and nitrogen is known among bright extragalactic planetary nebulae. Notably, in dwarf irregular galaxies, where high mass progenitor stars of planetary nebulae are reasonably expected, many bright planetary nebulae have low N/O ratios, which argues against the progenitors of these planetary nebulae having had a large initial mass (Richer & McCall 2007). Finally, no models explain the scatter in nitrogen enrichment found. Unfortunately, the nitrogen abundances are based upon observations of minority ions, so these results are more uncertain than is desirable. If correct, however, theses nitrogen abundances imply that low- and intermediate-mass stars are a much more significant source of nitrogen production than has hitherto been thought.

III. EXPANSION VELOCITIES

Richer (2006) and López et al. (2006) provide a preliminary summary of the expansion velocities observed in bright extragalactic planetary nebulae. As Fig. 1 indicates, what is most noticeable is the uniformity of the expansion velocities, independent of the age or metallicity of the stellar populations from which these planetary nebulae arise. Typically, the expansion velocities observed in a given galaxy average about 18 km/s and span a range of 8-28 km/s. Here, the expansion velocity is defined as the half-width at half maximum of the line profile. Except for those objects with the highest signal-to-noise observations, the line profiles are indistinguishable from a Gaussian profile. Within M31, however, there appears to be a clear statistical difference between the expansion velocities observed for the bright planetary nebulae in its bulge and those in the outer disk, with those in the bulge expanding slightly faster. The statistical significance of this result exceeds 99%. At a slightly lower significance, the same difference is found for bright planetary nebulae from old and young stellar populations, with those from old populations expanding slightly faster. The only clear correlation of expansion velocities with global spectral properties is that all of the objects with the largest Hβ luminosities have small expansion velocities.

The expansion velocities of bright extragalactic planetary nebulae confirm the youth of these objects. The range of expansion velocities observed overlaps that found for the expansion of the envelopes of AGB stars. Likewise, the lack of large expansion velocities at the largest Hβ luminosities argues that the expansion velocities are initially low and increase with time. The Gaussian or nearly-Gaussian line profiles (typical and highest signal-to-noise, respectively) also argue that the objects are likely to be young, as hydrodynamical models predict considerable material at low velocities at this stage of evolution (Villaver et al. 2002; Perinotto et al. 2004).

It may also not be unusual that the planetary nebu-

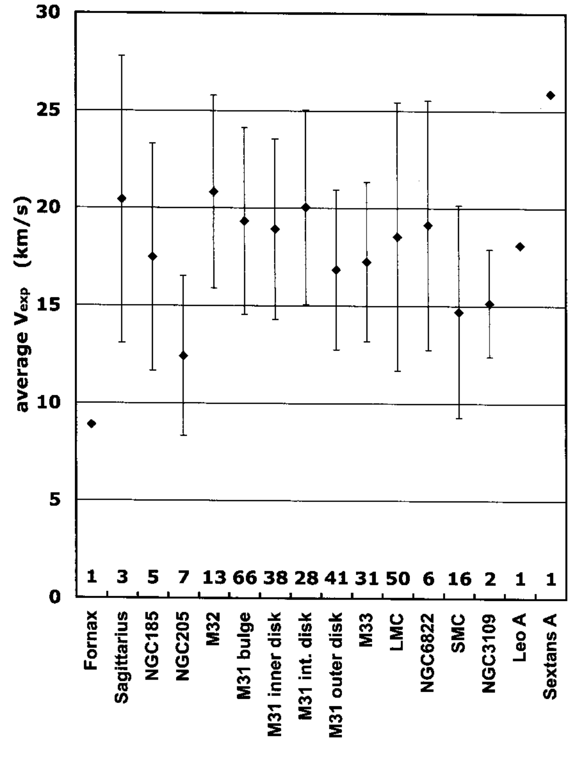

Fig. 1.— For each galaxy, or galactic component in M31, the mean expansion velocity for planetary nebulae is plotted as a filled symbol. The error bars indicate the standard deviation of the velocity distribution about the mean value. The numbers at the bottom of the plot indicate the number of planetary nebulae in each sample. Old stellar populations are on the left in order of increasing metallicity (from Fornax to the bulge of M31). Young stellar populations are on the right, plotted in order of decreasing metallicity (from the inner disk of M31 to Sextans A).

lae arising from old stellar populations have larger expansion velocities than those arising from young stellar populations. Hydrodynamical models (Villaver et al. 2002) indicate that the expansion velocity observed while planetary nebulae are brightest is not a monotonic function of mass and allow larger expansion velocities from the bright planetary nebulae arising from the lower mass progenitors from older stellar populations.

Finally, the similar range of expansion velocities observed for bright planetary nebulae regardless of the age or metallicity of the progenitor stellar population is compatible with the low masses deduced from analyses of their chemical composition. Essentially, the wider the range of masses for the progenitors of bright planetary nebulae, the wider the range of expansion velocities should be since the energy available for ejecting the envelope is ultimately a function of the luminosity of the progenitor star, and the luminosity scales with the mass. That a similar range of velocities is found in all galaxies and that a small range of velocities is found at the largest Hβ luminosities argue that the range of masses involved is probably not extremely large.

IV. FINAL CONSIDERATIONS

From the foregoing, it might be tempting to suppose that all bright extragalactic planetary nebulae arise from very similar stars in all galaxies, but this is unlikely. First, the chemical compositions of bright planetary nebulae trace those of the stellar populations in their host galaxies. Thus, bright planetary nebulae span abundances exceeding a factor of 10 among the galaxies for which adequate spectroscopy exists for their planetary nebulae. Since the chemical composition of a star influences the nucleosynthetic and dredge-up processes that take place during its evolution, this range in chemical composition likely dictates that the progenitor stars of bright planetary nebulae in different galaxies span different mass ranges.

Second, as both Stasińska et al. (1998) and Richer (2007) have argued, the spectroscopic properties of bright planetary nebulae arising from young and old stellar populations differ. Normally, this difference is interpreted in terms of a difference in the distribution of the masses of the central stars, but it may also arise from differences in the masses of the nebular shells or central star envelopes (Stanghellini & Renzini 2000), or from a combination of both effects.

Finally, it is well-known that planetary nebulae arising from old stellar populations are much more efficient emitters of [O III]λ5007 than are their counterparts in young stellar populations (Richer et al. 1999; Méndez et al. 2005). This likely reflects a difference in the ionization structure of the nebular shells (Stasińska et al. 1998).

Therefore, both the chemical compositions and expansion velocities of bright planetary nebulae in different galaxies argue that their progenitor stars did not differ dramatically. Nonetheless, the expansion velocities and spectral properties indicate that there are likely some significant differences. Differences in the central stars or the evolution of the nebular shell could easily arise as a result of different distributions of initial masses for the progenitor stars in young and old stellar populations. There would appear to be several pathways to producing bright planetary nebulae.

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