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THE PLANETARY NEBULA LUMINOSITY FUNCTION

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RESUMEN

Se presenta una breve introducción al tema de la función de luminosidad de las nebulosas planetarias (PNLF) y su uso para la determinación de distancias extragalácticas. Se describen las características esenciales del método utilizado por Jacoby, Ciardullo, Ford y otros para obtener la PNLF observada, y para determinar distancias. A continuación se provee una lista de objeciones al método, y se las discute mediante la introducción de un procedimiento sencillo para la simulación numérica de la PNLF. Se encuentra que la magnitud absoluta del extremo más brillante de la PNLF está afectada por el tamaño de la muestra, por las características de la población estelar, y también por el grado de espesor óptico que la nebulosa presenta a la radiación ionizante emitida por la estrella central. Aunque estos efectos pueden significar que el método es menos preciso que lo pensado originalmente, se encuentra que las distancias de Jacoby, Ciardullo et al. no requieren correcciones importantes. En particular se vuelve a obtener una distancia de 15 Mpc para el cúmulo de Virgo.

ABSTRACT

This talk gives a brief introduction to the subject of the planetary nebula luminosity function (PNLF) and its use for extragalactic distance determinations. After describing the essential features of the early work by Jacoby, Ciardullo, Ford and collaborators, a list of objections is given. The relevance of these objections is analyzed using a simple procedure for the numerical simulation of the PNLF. The bright end of the PNLF turns out to be affected by sample size, by population characteristics and by the extent to which stellar ionizing photons are able to escape unabsorbed by the nebula. Although the PNLF method may be less accurate than previously thought, the distances determined by Jacoby, Ciardullo et al. are not significantly affected; in particular, the PNLF method still gives a distance of 15 Mpc to the Virgo cluster.

Key words: **DISTANCE SCALE — PLANETARY NEBULAE — STARS – LUMINOSITY FUNCTION, MASS FUNCTION**

1. INTRODUCTION

The [O III] λ5007 planetary nebula luminosity function (PNLF) has attracted much interest after its introduction as a tool for the systematic determination of extragalactic distances. Jacoby, Ciardullo, Ford and collaborators have studied the PNLF in more than 20 galaxies at different distances, from the LMC to the Virgo cluster (Jacoby and Ciardullo 1992). A recent review of the PNLF method, among other methods for extragalactic distance determinations, is given by Jacoby et al. (1992); see also van den Bergh (1992). Here I present a very brief introduction to the subject, describing the essential features of the early work and some objections that have been formulated in the literature. In order to analyze these objections it is convenient to generate a theoretical PNLF. I describe a simple procedure for the numerical simulation of the PNLF, and discuss the shape and physical interpretation of the PNLF, as well as the technique to be applied for distance determinations. A more detailed discussion of these matters can be found in Méndez, Kudritzki, Ciardullo and Jacoby 1993, Astron. Astrophys., submitted.

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2. EXTRAGALACTIC PLANETARY NEBULAE AND THE OBSERVED PNLF

The identification of PNs in other galaxies is normally made by comparing two CCD images: one taken through a narrow filter (FWHM $\sim$ 30 Å) centered at the redshifted wavelength [O III] λ5007, and another one taken through an "off-band" filter at a nearby wavelength ($\sim$ 5300 Å). The off-band image is scaled to, and then subtracted from, the on-band image, until the background continuum is minimized. In principle, we are then left with isolated images of emission-line sources. Photometric measurements and calibrations (accomplished using images of standard stars) give the [O III] λ5007 fluxes. Most of the current work on the PNLF, particularly at large distances, is restricted to early-type galaxies (ellipticals, etc.) and halos of edge-on spirals, in order to avoid contamination with H II regions ionized by massive Population I stars.

For easier work with distance moduli, it is convenient to transform [O III] fluxes into magnitudes. Jacoby (1989) introduced the following definition:

$$m(5007) = -2.5 \log I(5007) - 13.74 \qquad (1)$$

where $I(5007)$ is the dereddened nebular flux, expressed in erg cm^{-2} s^{-1}, and the constant 13.74 is derived from the monochromatic flux of a star with V=0, and from the equivalent width of the Johnson V filter. For example, the brightest PN in M 31 (Ciardullo et al. 1989a) has $m(5007)$=20.0, after correcting for the foreground extinction. For a distance of 770 kpc ($m - M = 24.43$) we obtain an absolute magnitude $M(5007)$=-4.43. Eq. (1) can be applied also to nebular H_β fluxes, giving magnitudes m_β and M_β.

The PNLF describes how many PNs there are at each value of $m(5007)$. Unfortunately it is not just a matter of counting, because the counts must be restricted to a statistically complete sample. The reason for this restriction is that the detectability of a PN varies with the background surface brightness. If we want a sample which is statistically complete down to a certain limiting brightness, we must ascertain that we are not ignoring PNs brighter than the limit.

What is the criterion for completeness? Renzini and Buzzoni (1986) have shown that the stellar death rate per unit luminosity (stars yr^{-1} $L_\odot^{-1}$) is quite insensitive to the age and initial mass function of the population. Hence, if the PN formation rate is similar to the stellar death rate, then the probability of finding a PN at any location in a galaxy should be roughly proportional to the surface brightness of the galaxy at that location.

Having selected a limiting magnitude, we can verify if the required proportionality is obtained. If we find a region of the galaxy where fewer PNs have been detected than expected from the surface brightness, then our sample is incomplete. Now we have two choices: either we select a brighter limiting magnitude and try again until we find proportionality everywhere, or we exclude from the total sample all PNs in the incomplete region.

After the total sample of discovered PNs has been reduced to a statistically complete sample, we can count PNs and plot the PNLF. Jacoby, Ciardullo, Ford et al. have done this for more than 20 galaxies. It turns out that the shape of the bright end of the PNLF is always very similar. It has been represented by an exponential function with a "cutoff" on the bright side. The absolute magnitude of the cutoff ($M(5007) \sim -4.5$) apparently is invariant enough to be useful as a secondary standard candle for extragalactic distance determinations. Metallicity effects are of minor importance. The calibration of the method was made using a large sample of PNs in M 31, avoiding in this way the persistent uncertainties associated with the distances to our Galactic PNs (besides, it is very difficult to achieve statistical completeness *within* our Galaxy).

The PNLF method has given very promising results: good agreement with the Cepheid distances to the Large Magellanic Cloud and M 81, and good internal agreement in groups like Leo I or the Virgo cluster, where different galaxies give essentially the same distances. See Jacoby et al. (1992).

3. A LIST OF OBJECTIONS

The shape and physical interpretation of the PNLF, as well as the technique to be applied for distance determinations, are still matters of some controversy (Sandage and Tammann 1990, Bottinelli et al. 1991, Tammann 1992). The most important objections are the following:

(a) The absolute magnitude of the cutoff may depend on the size of the PN sample; a larger sample would be expected to show a few brighter PNs.

(b) If the bright end of the PNLF has a pure exponential shape, it may be hard to make a simultaneous determination of distance and sample size, because the solution may be ambiguous. For example, it might be difficult to distinguish between a small galaxy with few PNs, and a more distant, larger galaxy with a more numerous population of PNs; which, given (a), would lead to the detection of intrinsically brighter PNs than in the small galaxy.

(c) The shape and position of the cutoff may depend on the age of the population, through the mass and L of the stars which are now evolving along the post-AGB tracks; a younger population, with a higher turnoff mass, would be expected to produce brighter PNs.

4. ANOTHER OBJECTION

To the arguments listed in the previous section I would add another one. The interpretation of the observed PNLF has been based on the assumption that all the brightest PNs in any galaxy must be completely optically thick in the H Lyman continuum, which means that all the stellar ionizing photons are absorbed by the PN. However, now we have strong evidence that this is not always the case. Méndez et al. (1992) have shown that 16 out of 23 PNs, in a sample of Galactic PNs characterized by luminous central stars, are optically thin. If we define an "absorbing factor" μ giving the fraction of stellar ionizing luminosity absorbed by the PN, then we find that, in the Galactic sample mentioned above, all PNs with luminous central stars hotter than about 40000 K have values of μ between 0.05 and 0.40. Clearly this is a factor to worry about.

One might argue that the evidence in our Galaxy is not compelling, because the sample is very small. But a similar situation is found in the Magellanic Clouds. Consider the nebular H_β fluxes. In Figure 4a of Dopita et al. (1992) we find that two of the eight "H_β-brightest" Magellanic Cloud PNs have excitation classes lower than 2, and only two of the eight have excitation classes higher than 4. This can be compared with the fact that all the 13 PNs with the brightest [O III] fluxes have excitation classes higher than 4 (see Figure 4b of the same paper). What is the meaning of this difference? For constant luminosity along a H-burning post-AGB track, the number of ionizing photons from the central star increases roughly by a factor 2.5 as we increase $T_{\rm eff}$ from 30000 to 70000 K. If the nebulae were completely optically thick, we would expect H_β fluxes brighter by a similar factor. But this is not what we see; in order to keep the low-excitation PNs among the brightest in H_β, we need to impose $\mu < 0.4$ for $T_{\rm eff} > 40000$ K, which is more or less the same we found in our Galaxy. Let us call $\mu_{\rm max}$ this maximum value of μ at high central star luminosities and temperatures. If the central stars are burning He instead of H, we can increase $\mu_{\rm max}$, but not beyond 0.7 (see evolutionary tracks in Wood and Faulkner 1986).

5. MODELING THE PNLF

In order to deal with all these objections, it is convenient to generate a theoretical PNLF in such a way that sample size, population age and partial absorption of stellar ionizing photons can be systematically studied. I have followed a simple approach which is characterized by the avoidance of nebular models. The reason for this choice is that nebular modeling requires several dangerous assumptions about expansion velocities, total nebular mass and its spatial distribution, and the behavior of nebular density as a function of stellar post-AGB "age". In fact, the last two characteristics are very poorly known. This would introduce large uncertainties in the predicted optical thickness, which is one of the key parameters we want to study. Consequently, the selected approach is tied, as much as possible, to *observed* properties of PNs and their central stars.

The procedure for the numerical simulation of the PNLF begins with the generation of a family of PNs with random ages and central star masses. The ages are given by a uniform random distribution between 0 and 30000 years. These ages are counted from the moment when the central star has $T_{\rm eff} = 25000$ K. In this way, all uncertainties related to "transition times" from the AGB are avoided. The masses are given by an exponential random distribution, following

$$N(m) = A \exp(B(m_0 - m)) \tag{2}$$

where m_0, m are masses (in solar masses) and $B = 12.5$. I adopt $m_0 = 0.55$ (below this mass no visible (1979) with a constant star formation rate (SFR) and the initial-to-final mass relation suggested by Weidemann (1987). I would remark that this central star mass distribution is wider than the one used by Jacoby (1989) in his modeling of the PNLF.

For each PN we have, then, a pair of random numbers giving mass and age of the central star. These random numbers are introduced into a routine containing an analytic approximation of post-AGB evolution, based on H-burning tracks from Schönberner (1989) and Blöcker and Schönberner (1990). The routine produces the luminosity and $T_{\rm eff}$ of each central star. This information permits to calculate (using recombination theory) the H_β luminosity that the nebula would emit if it were completely optically thi in the H Lyman continuum. From the flux that would be measured at a distance of 10 pc we obtain directly M_β. But this M_β must be corrected to allow for partial absorption of stellar ionizing photons. This is made by generating a third random number for each PN, which gives the absorbing factor μ, constrained to specific values in different regions of the log L - log $T_{\rm eff}$ diagram. The constraints are derived from the information collected by Méndez et al. (1992). In particular, in the critical region of high stellar luminosity and temperature, μ is given by a uniform random distribution between 0.05 and an adjustable parameter $\mu_{\rm max}$.

Having calculated the corrected H_β fluxes, we only need to produce values of the intensity ratio 5007/H_β. For that purpose it is also possible to rely on the observational evidence: from work by Stasinska (1989, see her Fig. 13) we find that the observed distribution of the ratio 5007/H_β can be reasonably approximated by a uniform random distribution between 900 and 1500 (on the usual scale of $H_\beta = 100$) plus a certain number of lower values which have a clear physical interpretation and can be modeled as a function of central star properties (more details in Méndez et al. 1993). In this way we can produce the desired values of $M(5007)$ and construct the theoretical PNLF.

6. SAMPLE SIZE, POPULATION AGE AND $\mu_{\rm max}$ EFFECTS

The numerical experiments just described produce PNLFs with the typical cutoff at the bright end. The slope of the cutoff is finite; therefore the absolute magnitude of the cutoff, at the level of detection of one object, becomes brighter with larger sample sizes, as suggested in objection (a). For example, take a PNLF calculated with $\mu_{\rm max} = 0.65$, and corresponding to 1000 objects, which predicts detection of one object at $M(5007) = -4.5$; if we increase the sample to 10000 objects, then the PNLF predicts 10 objects at -4.5 and one object at -4.9. The cutoff does not have a pure exponential shape; in the usual plot (log number versus $M(5007)$) the cutoff is not describable by a straight line, because the slope changes as a function of sample size at any given log number. Therefore, in principle it is perfectly possible to make a simultaneous determination of distance modulus and sample size. This means we can disregard objection (b).

Concerning objection (c), remember that the central star mass distribution we used to model the PNLF was built on the assumption of a constant SFR. Assume now that star formation stopped some time ago. There will be a turnoff mass corresponding to the time elapsed since the last star formation. Roughly speaking, all stars more massive than this turnoff have already gone through the PN phase. Taking into account the width of the initial-to-final mass realtion, we can estimate the maximum final mass of the dying stars. The corresponding PNLF can be simulated by rejecting, from the central star mass distribution, all stars more massive than the maximum final mass. A PNLF corresponding to an older population turns out to have a fainter cutoff, corresponding to a lower maximum final mass. At the same time the cutoff has a steeper slope, which means that older ages help to decrease the importance of the sample size effect. For example, take again $\mu_{\rm max} = 0.65$ and assume a maximum final mass of 0.63 solar masses; now for 1000 and 10000 objects the detection of one object is predicted at -4.3 and -4.5, respectively.

The absolute magnitude of the cutoff is also affected by the value of $\mu_{\rm max}$; two PNLFs with $\mu_{\rm max} = 0.65$ and 1.0 have cutoffs separated by about 0.4 mag. Obviously the larger $\mu_{\rm max}$ is associated with the brighter cutoff.

7. TESTING AND USING THE SIMULATED PNLF

In order to test if these simulated PNLFs can fit the observed ones, we start by the LMC, which has a well-known distance of 50 kpc, shows abundant evidence of recent star formation, allowing us to assume a constant SFR, and must have a $\mu_{\rm max}$ between 0.4 and 0.7, as mentioned above. Taking $\mu_{\rm max}$ as an adjustable parameter, it is indeed possible to obtain a good fit to the bright end of the observed PNLF (Jacoby et al. 1990b), for the right distance and $\mu_{\rm max} = 0.6$, well within the expected range. Therefore the new procedure for the numerical simulation of the PNLF does seem to produce reasonable results.

Consider now the bulge of M 31 (Ciardullo et al. 1989a), a population showing no evidence of recent star formation. Adopting a maximum final mass of 0.63 solar masses, again a good fit is obtained for a distance of 770 kpc and $\mu_{\rm max} = 0.84$. The estimated sample size in this case is 1200 objects; this is the total amount of PN predicted to exist in the surleyed region of M 31.

What are the practical consequences for extragalactic distance determinations? Since most of the previous work was restricted to early-type galaxies and bulges and halos of spirals, we are always talking about a rather old population, with last star formation taking place between 5 and 15 Gyr ago. Then presumably a maximum final mass between 0.61 and 0.64 solar masses is adequate, unless there is substantial evidence of recent star formation. Concerning μ_{max}, I would adopt 0.8 as a working hypothesis. The good internal agreement obtained for different galaxies in the Virgo cluster by Jacoby et al. (1990a), and in the Leo I group by Ciardullo et al. (1989b), would seem to indicate, somewhat surprisingly, that there may be a typical value of μ_{max} applicable to most early-type galaxies. But clearly this is a problem that requires further work; our lack of knowledge about μ_{max} adds uncertainty to the distance determinations.

In the present situation I estimate that the PNLF method produces distance moduli with typical error bars of about ± 0.4 mag. This is less accurate than previously thought, but good enough to obtain very useful information. A rediscussion of the distance to the Virgo cluster, using the same data as published by Jacoby et al. (1990a), and using the same PNLF as for M 31 above, produces a distance modulus $m - M = 30.9 \pm 0.4$, almost the same as determined by Jacoby et al. (1990a). The estimated sample size is 12500, roughly 10 times the sample size in M 31, and accordingly we do find in the Virgo cluster some PNs brighter than the brightest one in M 31. The error bar in the distance modulus includes the most extreme assumptions we can make about μ_{max} and the maximum final mass (1.0 and 0.66 solar masses, respectively). In summary, after taking into account all the objections to the earlier formulation of the PNLF method, it still gives a distance of 15 Mpc to the Virgo cluster.

8. CONCLUSIONS

Although several improvements in the numerical simulation of the PNLF are still possible, the simple procedure described here already permits to conclude the following:

(a) The absolute magnitude of the bright end of the PNLF is affected by sample size, by population characteristics and by the extent to which stellar ionizing photons can escape unabsorbed by the nebula.

(b) The PNLF method of distance determinations may turn out to be less accurate than previously thought. In particular we need to learn more about μ_{max} in different galaxies. On the other hand, the sensitivity of the PNLF to the maximum final mass of the population may open the possibility of learning about that parameter in different galaxies, telling us something about the width of the initial-to-final mass relation and therefore about mass loss processes on the AGB.

(c) Despite the possible loss in accuracy, the PNLF method still produces useful distances, at least to within ± 0.4 mag, and it still gives a distance of 15 Mpc to the Virgo cluster.

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