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PLANETARY NEBULAE AS STANDARD CANDLES. VIII. EVIDENCE FOR A CHANGE IN THE LUMINOSITY FUNCTION CUTOFF AT LOW METALLICITY

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ABSTRACT

We search for a change in the [O III] λ5007 planetary nebula luminosity function (PNLF) with metallicity by combining the planetary nebula (PN) observations of four metal-poor galaxies in the Local Group: M32, NGC 185, NGC 205, and the Small Magellanic Cloud. We show that the most likely magnitude cutoff for the PNs in our sample is $0.28^{+0.11}_{-0.17}$ mag fainter than the value of M^* observed in the bulge of M31, but consistency with the M31 measurement cannot be ruled out beyond the 70% confidence level. The data suggest that PN–based distances may depend slightly on the underlying stellar population, with a factor of 10 in metal abundance translating into an apparent shift in the value of M^* by 0.25 mag ($D(\mathrm{PNLF}) \propto Z^{-0.05}$). However, because this variation is small, and population differences among luminous early-type cluster galaxies are usually slight, the effect is not important for cosmological distance determinations. The observed shift in the luminosity function is in good agreement with the theoretically derived metallicity dependence of Dopita, Jacoby, & Vassiliadis.

Subject headings: galaxies: distances and redshifts — galaxies: luminosity function, mass function — Local Group — planetary nebulae: general

1. INTRODUCTION

Planetary nebulae (PNs) are among the best extragalactic standard candles. They are bright, easy to measure, apparent in all galaxies, and can be found far away from dust and star-forming regions. Best of all, the planetary nebula luminosity function (PNLF) appears to be extremely insensitive to the parent stellar population. In the Leo I and Virgo Clusters, the derived distances to early-type galaxies all agree to within 5%, despite differences of 0.19 in [Fe/H], 0.3 mag in $(U-V)$ color, and 2.2 mag in the ultraviolet flux index $(m_{1550}-V)$ (Ciardullo, Jacoby, & Ford 1989a; Jacoby, Ciardullo, & Ford 1990a). In the NGC 1023 Group, the derived distance to the planetaries in the disk of the gas-rich S0 galaxy NGC 1023 is identical to that estimated for the PN in the halo and outer bulge of the edge-on Sbc spiral NGC 891 (Ciardullo, Jacoby, & Harris 1991). Even in the Large Magellanic Cloud, there is no evidence for any change in the PNLF. Despite the fact that the LMC is a metal-poor star-forming Sdm/Im galaxy, the distance ratio between it and M31, as derived from planetaries (Jacoby, Walker, & Ciardullo 1990b) is identical to that computed from the observation of Cepheid variables (Welch et al. 1986, 1987; Feast & Walker 1987).

Despite these facts, the PNLF is probably not *completely* independent of stellar population. In a planetary nebula, both the UV flux from the central star (Lattanzio 1986; Brocato et al. 1990) and the [O III] λ5007 emission from the nebula (Jacoby 1989) depend on metallicity, and, while the two processes affect the derived distance in opposite senses, it is unlikely that they cancel out completely. Likewise, a PN central star's UV flux depends strongly on its mass (Paczyński 1971; Schönberger 1981, 1983; Wood & Faulkner 1986), and although the mass of the final remnant may be very insensitive to the progenitor's turn-off mass (Ratag, Walters, & Pottasch 1991; Blöcker & Schönberner 1990), some dependence probably exists (Weidemann & Koester 1983). In fact, the observations of Jacoby et al. (1990b) do suggest that for the extreme population of the SMC, the PNLF cutoff is systematically fainter by ~0.33 mag than that observed in the bulge of M31, but due to the sparseness of the function this difference is not statistically significant.

Testing for changes in the PNLF in extreme populations is difficult, especially if one wants to examine the dependence of the PNLF on metallicity. Most metal-poor systems are low-mass objects with very few bright planetaries; hence their PNLFs are not very well defined. For example, the dwarf elliptical NGC 185 has just four planetaries populating the top ~2.5 mag of the luminosity function. NGC 205 has only 12 objects in this range; the SMC only 17. In none of these galaxies is the PNLF defined well enough to allow a reliable distance estimate for comparison with other methods. However, if the luminosity functions of these galaxies could be co-added, the resulting PNLF would be accurate enough for a meaningful comparison. In this paper, we perform such an addition and show that the PNLF may indeed depend slightly on the metallicity of the underlying stellar population.

2. CREATING A COMPOSITE LUMINOSITY FUNCTION

To form our composite PNLF, we began by adopting the observed [O III] λ5007 magnitudes for PN in the SMC (Jacoby et al. 1990b), M32, NGC 185, and NGC 205 (Ciardullo et al. 1989b). We then corrected each set of magnitudes for foreground extinction by combining the extinction estimates appropriate to each galaxy with the Seaton (1979) reddening

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law. For the SMC, we chose $E(B-V) = 0.06$ to represent the mean differential extinction toward each planetary (Jacoby et al. 1990b); for M32, NGC 185, and NGC 205, we used the Burstein & Heiles (1984) estimates for A_B of 0.32, 0.78, and 0.14 mag, respectively.

We next converted our dereddened apparent magnitudes to absolute λ5007 magnitudes using current estimates for the distance moduli for each galaxy. For the SMC, we chose a distance modulus of $\mu_0 = 18.76$ based on the review by Feast (1988); for NGC 185, we adopted the RR Lyr distance modulus of 23.79 found by Saha & Hoessel (1990). We assumed the true distance modulus to M32 and NGC 205 to be the same as that for M31, $\mu_0 = 24.26$ (Welch et al. 1986). Following Ciardullo et al. (1989b), our PN magnitudes are related to the flux at 5007 Å by

$$M_{5007} = -2.5 \log F_{5007} - 13.74 . \quad (1)$$

Figure 1 displays the absolute [O III] λ5007 PNLF for our synthetic metal-poor galaxy, assuming an incompleteness limit derived from the M31 dwarfs of $M_{\rm lim} = -1.95$ (Ciardullo et al. 1989b). Although the function is still sparsely populated, it is apparent that the shape of the PNLF is consistent with that found in every galaxy surveyed to date, with

$$N(M) \propto e^{0.307M}[1 - e^{3(M^*-M)}] . \quad (2)$$

However, an examination of the function also suggests that the cutoff magnitude for PNs in the synthetic galaxy is slightly fainter than the $M^* = -4.48 \pm 0.04$ observed in the bulge of M31 (Ciardullo et al. 1989b).

To quantify the change in M^*, we used the method of maximum likelihood described in Ciardullo et al. (1989b). To do this, we first determined an "error function" to represent both the photometric uncertainty in the PN measurements and the line-of-sight depth of the SMC. As a compromise between the relatively small photometric errors associated with the bright PNs of the Local Group dwarfs (Ciardullo et al. 1989b), and the large spread of distances expected from SMC PNs (Feast 1989; Jacoby et al. 1990b), we adopted 0.1 mag as the

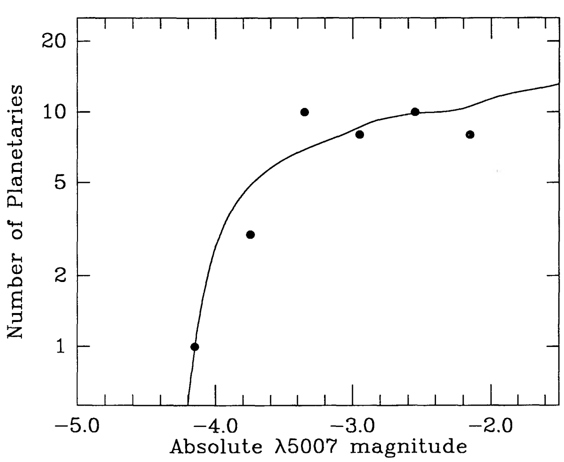

FIG. 1.—The planetary nebula luminosity function of a metal-poor population, formed from observations of PNs in M32, NGC 205, NGC 185, and the Small Magellanic Cloud. The data are binned into 0.4 mag intervals. The solid lines show the best-fit empirical PNLF convolved with the mean photometric error vs. magnitude relation. (The slight inflections in the curve are due to the rapidly increasing photometric errors at fainter magnitudes.) The most likely value for the PNLF cutoff is $M^* = -4.20$, 0.28 mag fainter than that derived from PNs in the bulge of M31.

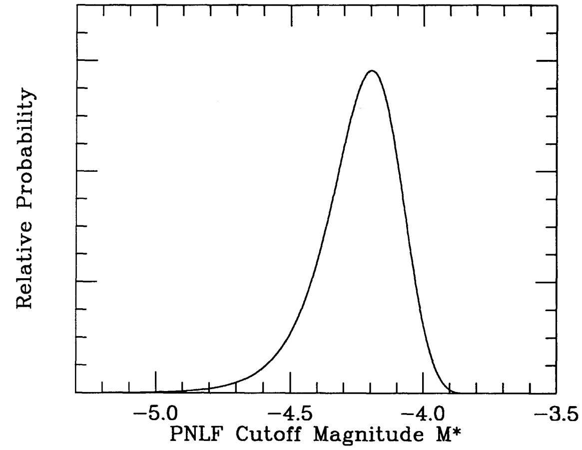

FIG. 2.—The results of the maximum likelihood analysis for the PNLF of M32, NGC 205, NGC 185, and the SMC. The abscissa is the implied value of the PNLF cutoff, M^*. The ordinate is the probability that the synthesized luminosity function has the given value of M^*. The most likely solution gives an M^* that is 0.28 mag fainter than the value of −4.48 observed in M31, but the possibility that the two luminosity functions are identical cannot be ruled out.

error appropriate for PN with $M_{5007} < -2.75$ and gradually increased this number to 0.2 mag at our magnitude limit of $M_{5007} = -1.95$. We then convolved this function with the luminosity function expressed in equation (2) and computed, as a function of M^*, the probability that our composite luminosity function is drawn from the empirical function. This probability curve is shown in Figure 2; the best-fit luminosity function is drawn in Figure 1. The most likely value of M^* for our metal-poor population is $-4.20^{+0.11}_{-0.17}$ and 93% of the probability lies below the nominal value of $M^* = -4.48$. Is this 0.28 mag difference significant? A Kolmogorov-Smirnov test cannot rule out the possibility that there is no variation in the PNLF, even at the 70% confidence level. Hence even in these extreme stellar populations, the PNLF continues to be a very good standard candle; if we were to derive a distance to our composite metal-poor galaxy based on the PNLF of M31, we would overestimate the distance to the system by $\lesssim 14\%$.

3. DISCUSSION

M32, NGC 185, NGC 205, and the Small Magellanic Cloud are all small galaxies with low metal abundances, and as such, the above analysis has some validity. However, the stellar populations in these galaxies are by no means homogeneous. M32 has a mean metallicity [Fe/H] ∼ −0.65, but the observed dispersion about this mean is large, ∼0.5 dex (Freedman 1989). The same is true for NGC 205—although the mean value for [Fe/H] in NGC 205 is ∼ −0.85, the scatter about this mean is more than 0.5 dex (Mould, Kristian, & Da Costa 1984). Moreover, the center of NGC 205 has ongoing star formation, indicating that a mix of stellar ages is present in the galaxy. NGC 185 appears to have a slightly smaller scatter (0.2 dex) about its mean abundance of [Fe/H] ∼ −1.05, but like NGC 205, the galaxy exhibits some amount of star formation (Da Costa & Mould 1988). The most inhomogeneous population included in this survey, however, is that of the SMC. Like M32, NGC 205, and NGC 185, the stars of the SMC exhibit a significant spread of abundances about their mean metallicity of [Fe/H] ∼ −0.65 (Russell & Bessel 1989; Russell & Dopita 1990). However, most of the PNs in the SMC probably come from the Population I component and are thus younger than the PNs of the small ellipticals. Therefore, although the luminosity function of Figure 1 is primarily that of a metal-poor population, the distribution cannot be considered to be homogeneous either in age or metallicity.

Nevertheless, if we treat the composite luminosity function as representative of a stellar population that is the metal-poor counterpart to M31's bulge, we can quantitatively compare our results to those predicted from models. The mean metallicity of the synthetic galaxy formed from M32, NGC 185, NGC 205, and the SMC is about 0.18 that of the Sun, or [Fe/H] ~ -0.75. The bulge of M31, which provides the PNLF calibration, is more than 11 times this value, with [Fe/H] ~ 0.3 (Burstein et al. 1988 calibrated by Terlevich et al. 1981). Since the luminosity function of Figure 1 suggests that our metal-poor population has a PNLF cutoff that is 0.28 mag fainter than the nominal value of M^*, this implies that M^* changes by 0.25 mag over a factor of 10 in metallicity.

The simplest way to model the expected behavior of the PNLF with metallicity is to consider a planetary's nebula and central star as two independent objects and calculate the effects of abundance variations on each. For the nebula, the amount of $\lambda5007$ emission depends on the number of oxygen atoms, and thus a decrease in metallicity lowers the emergent flux. However, because oxygen is one of the principal coolants of the nebula, this decrease is partially mitigated by an increase in the amount of emission per ion caused by the higher nebular electron temperature. Hence, the [O III] $\lambda5007$ flux from a PN's nebula should be roughly proportional to the square root of metallicity (Jacoby 1989).

In order to estimate how a decrease in metallicity affects the ionizing flux of a PN's central star, it is necessary to use post–asymptotic branch evolutionary models. Both Lattanzio (1986) and Brocato et al. (1990) have investigated how metallicity affects the maximum luminosity attained by a hydrogen-exhausted core and have concluded that as the amount of metals in a star is decreased, the star's UV luminosity increases, with a factor of 2 decrease in metals resulting in a $\sim 30\%$ increase in UV flux. If we extrapolate this dependence to the metallicity of our synthetic galaxy and couple it with that expected from the nebula, then we would predict the value of M^* in our metal-poor system should be ~ 0.32 mag fainter than the M^* observed in the bulge of M31. This is in good agreement with what is observed.

A more sophisticated way of analyzing the effect of abundance variations on the PNLF is to compute a series of self-consistent post–asymptotic branch models, which include mass loss at all stages along the evolutionary path. This has been done by Vassiliadis & Wood (1991) and applied to the PNLF problem by Dopita, Jacoby, & Vassiliadis (1992). In their models, the effect of changing the amount of metals in a PN is neither linear nor monotonic, with the brightest values

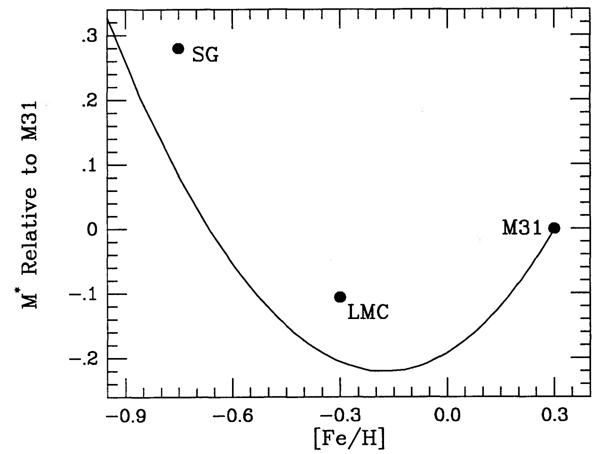

FIG. 3.—The predicted effect of metallicity on M^* based on the formulation of Dopita, Jacoby, & Vassiliadis (1991), assuming a population age of 8 Gyr. "SG" denotes our synthetic galaxy's position in the diagram. Note that the theoretical function is not monotonic and that the M31 metallicity represents a fortuitous compromise, effectively minimizing deviations in M^* due to metallicity variations among galaxies. Based on this figure, one would expect that the LMC PNLF would be ~ 0.2 mag too bright ([Fe/H] ~ -0.32; Russell & Dopita 1990), in fair agreement with the distance modulus of 18.44 ± 0.18 derived by Jacoby, Walker, & Ciardullo (1990) and the SN 1987A circumstellar ring result of 18.55 ± 0.13 (Panagia et al. 1991).

of M^* occurring at metallicities slightly less than solar. Thus, the models predict that the PNLF of our synthetic galaxy should be ~ 0.1 mag fainter than that observed for M31. This has the same sense as the observational result and is well within the uncertainties. However, it should be noted that according to the Dopita et al. theory, the shift in the luminosity function would have been greater had the synthetic galaxy been of near solar metallicity, rather than being very metal poor, since the predicted metallicity dependence is not monotonic (see Fig. 3).

Although the above analysis suggests that the PNLF does shift the metallicity of the underlying population, it should be stressed that the distance dependence is slight and not important for most extragalactic applications. If the dependence of M^* on [Fe/H] is linear, then the observed difference between the PNLF of M31's bulge and that of our metal-poor synthetic galaxy implies that PNLF distances only change with the 0.05 power of metallicity. Jacoby's (1989) nebular analysis, in combination with the post–asymptotic branch models of Lattanzio (1986) and Brocato et al. (1990), predicts a similar insensitivity [$D(\mathrm{PNLF}) \propto Z^{0.06}$], as does the analysis of Dopita et al. (1992) [$D(\mathrm{PNLF}) \propto Z^{-0.08}$ for $Z < Z_\odot$; $D(\mathrm{PNLF}) \propto Z^{0.11}$ for $Z > Z_\odot$]. Thus, when applied to metal-rich giant elliptical and S0 galaxies, the expected systematic errors introduced by these variations are only a few percent. This error is unimportant for PNLF measurements of the cosmic distance scale.

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