LARGE-SCALE STRUCTURE OF THE MAGELLANIC CLOUDS USING PLANETARY NEBULAE

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1. Introduction

The Small and Large Magellanic Clouds (SMC, LMC) are of considerable interest from a kinematical viewpoint. The tidal interation of the Clouds with each other and with the Galaxy appears to have been quite significant in recent times (Murai & Fujimoto 1980). The SMC in particular appears to have been considerably disrupted by a recent close passage to the LMC (Mathewson & Ford 1984, Mathewson 1984, Mathewson *et al.* 1986). For the LMC Freeman *et al.* (1983) found that the young and old populations have significantly different rotation solutions.

Planetary Nebulae (PN) form a population with age intermediate between the HI and young clusters and the old Population II clusters. A large number of PN are known in the MCs. Sanduleak *et al.* (1978) compiled a list of 102 in the LMC and 28 in the SMC. Since then other authors have increased the total number known to approximately 140 in the LMC and 50 in the SMC.

2. The Small Magellanic Cloud

The SMC has a confusing radial velocity field. In the 21-cm line of HI, a double peak structure with a velocity splitting of 30-40 km s^{-1} is apparent across much of the SMC (Mathewson & Ford 1984). This pattern is shared by the young stars, and the CaII H and K absorption velocities are found predominantly associated with the approaching component of the HI, suggesting that this is nearer in space (Mathewson & Ford 1984). Indeed, Mathewson and Ford claim that the SMC consists of two distinct subsections.

Dopita *et al.* (1985) presented kinematical data for 44 SMC PN. Their data consisted of [OIII]5007Å spectral data at a resolution (FWHM) of approximately 12 km s^{-1} with an associated error of less than 2 km s^{-1}. The most striking feature of these velocity data is that the PN population appears to be completely disordered. The PN form a loose and extended structure without a very strong central condensation. However, the centroid of the distribution at 00H 49M 30S -73° 20' (1950) agrees closely in position with the brightest region of the SMC Bar and the major axis aligned in a NE-SW direction also agrees with that of the Bar.

The hypothesis that we are dealing with a spheroidal population is supported by plotting the number of PN in bins of projected distance along the major axis. An isothermal distribution with

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space density proportional to $1/r^2$ would give a surface density $S \propto 1/R_{proj}$, and this is a satisfactory approximation to the observed density.

There is no evidence that the spheroidal population has an organized rotation. Fig. 1 (from Dopita *et al.* 1985) is a plot of observed velocity, corrected to galactocentric standard of rest (assuming circular rotation in the solar neighbourhood of 250 km s^{-1}), against the projected distance along the major axis. This diagram shows a lack of rotation, and also that the dispersion in velocity is effectively independent of position. As well, there is no evidence of the bimodal distribution in velocities previously suggested by Feast (1968) using 13 PN.

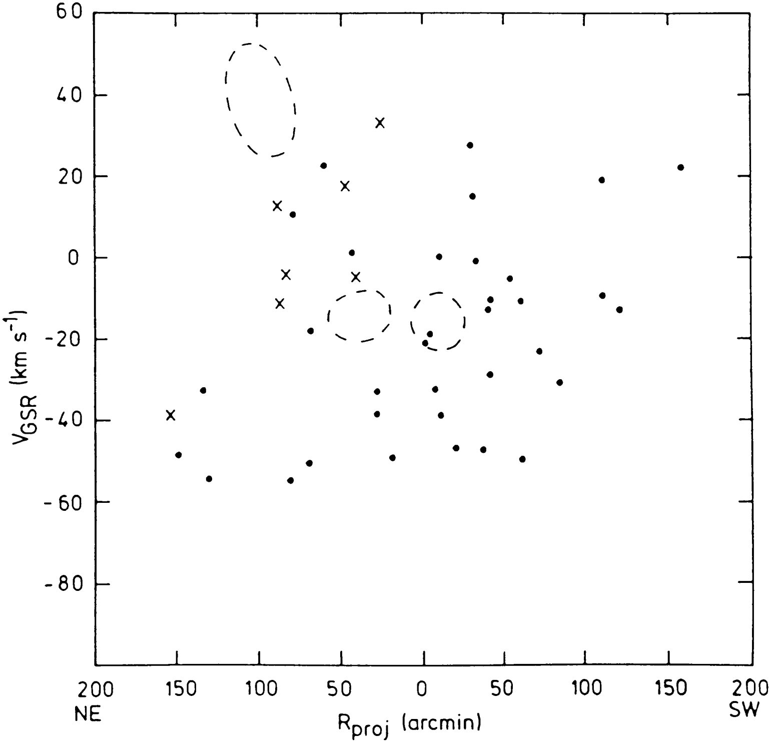

Figure 1. The observed galactocentric standard of rest velocity (V_{gsr}) plotted against the projected distance from the centroid along the major axis. The crosses represent the apparently younger population of planetaries. The dashed lines show the principal maxima in the HI distribution.

There is some evidence for a younger, high-velocity sub-population of PN concentrated in the NE sector of the SMC. Their age is implied by nebular spectral characteristics indicative of higher mass precursors, and are shown in Fig. 1 as 'X' to distinguish them from the other PN.

A comparison with the HI kinematics is instructive. Fig. 1 also shows the principal maxima seen in the HI. The mean velocity of the PN (V_{gsr}= -18.3 km s^{-1}) agrees well with the mean velocity of the lower velocity HI maximum (-15 km s^{-1}). If the older PN only are considered, the mean velocity is somewhat lower still (V_{gsr}= -22 km s^{-1}). Furthermore, many have velocities in the range -50 to -60 km s^{-1}, which is outside the range of all but a faint tail of HI.

The spatial location and velocity distribution of the younger PN is such that they cluster in a region of the SMC associated with a young stellar population (Mathewson & Ford 1984). They appear more closely associated with the higher velocity HI gas, and to have been shed from the HI at an earlier epoch.

Thus, there is good agreement with Mathewson and Ford (1984) in that the SMC appears to have been disrupted by tidal forces in the recent past. However, the PN data show that the effect of this has been quite different on the older stellar component and on the gas. The stellar component is roughly spherical, whereas the gaseous component has developed a tidal counter-arm moving away from us.

3. The Large Magellanic Cloud

Freeman *et al.* (1983) report finding that the young and old populations have significantly different rotation solutions; the old population of clusters has its line of nodes rotated by some 49° with respect to clusters with ages $<10^9$ years. Before 1988, only three kinematic studies of PN had been carried out (Feast 1968, Webster 1969, Smith & Weedman 1972), furnishing data on 35 objects. Meatheringham *et al.* (1988) presented velocity data for 95 objects, significantly expanding the sample. These latter data were of the same type and quality obtained by Dopita *et al.* (1985) for the SMC.

3.1 HI SURVEYS AND THE TRANSVERSE VELOCITY OF THE LMC

The HI data give a very useful young reference frome with which to compare and contrast the kinematics of the older PN population. The most suitable HI survey to data is that of Rohlfs *et al.* (1984) which gives velocities to a precision of ±1 km s^{-1} over a grid of >1000 points within the central 6° of the LMC.

The angular diameter of the LMC and its large transverse velocity (of order 300 km s^{-1}, e.g. Mathewson *et al.* 1977, Lin & Lynden-Bell 1982) ensure that there will be a substantial velocity gradient in the directio of motion. If the LMC is a rotating flat disk, the velocity gradient from the transverse motion will be combined with the rotation curve to change the maximum velocity gradient and twist the lines of constant velocity.

The plane defined by the Magellanic Stream and the Clouds defines the orbital plane of the Clouds. The correct value of the transverse velocity is found when, applying its inverse, it rotates the kinematic line of nodes to lie in the same direction as the photometric lines of nodes. Meatheringham *et al.* derive a value of 275 ± 50 km s^{-1} in a direction of position angle 110°, implying that the Magellanic Stream trails the LMC, and a ram-pressure stripping origin is favoured.

3.2 MASS AND ROTATION CURVE

From the Rohlfs *et al.* HI data a rotation curve can be determined using a strip of ±15° in position angle passing through the centroid of the PN distribution, and deprojected for an inclination of 33°. It is approximately symmetrical about $r=+0.5°$ and not the PN centroid. The central ±1.5° is strongly perturbed, possibly as a result of gas streaming motions expected from asymmetric positioning of the bar (de Vaucouleurs & Freeman 1972, Feitzinger 1983).

The best fit to the data (Fig. 2) assumes solid body rotation out to 2° from the centre of symmetry, with an exponential disk outside that. Fitting this composite model gives a mass out to ±3° of $(4.6\pm0.2)\mathrm{x}10^9\ M_\odot$, and if the disk continues out to 6° (approximately the largest size as given by HI observations) this implies a mass of $M_{LMC} = (6.1\pm0.5)\mathrm{x}10^9\ M_\odot$.

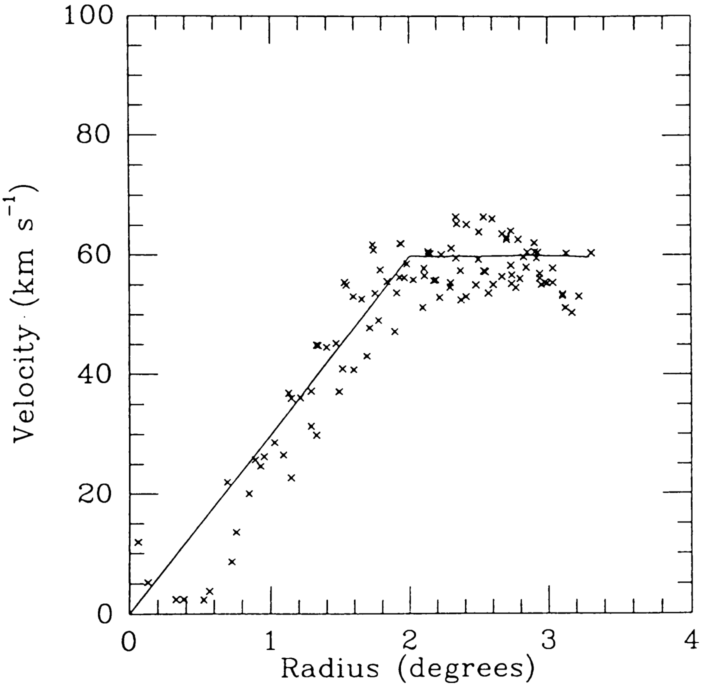

Figure 2. LMC rotation curve obtained after folding the HI data about the symmetrical point. The solid line represents the fitted theoretical curve comprising solid body rotation within the inner 2° together with an exponential disk outside that.

3.3 ROTATION SOLUTIONS FOR HI AND PN

It is of great interest to compare the PN and HI. The means to analyse the velocity data is derived from that given by Freeman *et al.* (1983). The rotation solution is given by:

$$V(\theta,r) = V_m(r)\left\{1 \pm \left[\tan(\theta-\theta_0)\sec i\right]^2\right\}^{-0.5} + V_0 \quad (0 \le \theta \le 2\pi)$$

where $V(\theta,r)$ is the rotational velocity projected onto the line of sight at position angle θ and radial coordinate r. The two free parameters are: θ_0, the position angle of the line of kinematic line of nodes for the LMC and V_0, the systemic Galactocentric velocity of the LMC. $V_m(r)$ is taken as the measured HI rotation curve.

Analysis gives θ_0=166° and V_0= 46 km s^{-1} for the HI solution, and θ_0 =170° and V_0=42 km s^{-1} for the PN. Fig. 3 shows, as a function of azimuthal angle, the velocity difference between the PN radial velocities, and the local HI radial velocities as compared with the rotation solution for the HI. Clearly, the velocity dispersion in the PN population is considerably higher than that of the HI. The typical line-of-sight velocity dispersion in the HI is 10 km s^{-1}, but there are distinct local regions of increased velocity dispersion. These correspond closely in position to supergiant shells of star-forming activity. By contrast, the PN velocity dispersion is constant and featureless with position angle.

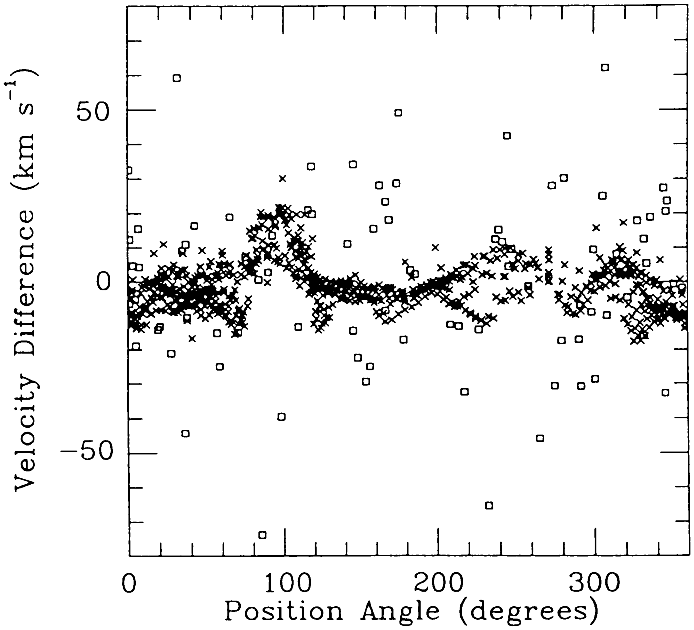

Figure 3. The velocity difference obtained from the HI data (crosses) and the planetary nebulae (squares).

We can conclude, therefore, that there is no significant difference between the HI and the PN kinematics other than an increase in velocity dispersion in the older PN population. This result confirms and amplifies that foreshadowed by Freeman *et al.* (1983), and poses an interesting conundrum. If, as claimed by them, the old clusters have a rotation axis that differs from the young solution by about 50°, how then could this have occurred? Such a tilt is not stable, and can persist only for a timescale of order 10^9 years. The most profound dynamical disturbance that may have been experienced by the LMC would have been a near-collision with the SMC that may have occurred about 2 x 10^8 years ago (Murai & Fujimoto 1980), resulting in profound tidal disturbance to the SMC (Mathewson & Ford 1984, Dopita *et al.* 1985, Mathewson *et al.* 1986). We conclude that either the PN population is younger than 2×10^8 years old or that this collision did not result in the twisting of the rotation axes implied by the old clusters.

3.4 ORBITAL DIFFUSION AND THE AGE OF THE PLANETARY NEBULAE

An increase in velocity dispersion is a natural consequence of a greater age. The process was examined by Spitzer and Schwartzchild (1951, 1953) who showed that orbital diffusion can occur as a consequence of "gravitational Fermi scattering" between stars and giant molecular clouds (GMCs). The relationship between total velocity dispersion at time t, $V(t)$, and the initial velocity dispersion, $V(0)$, of a stellar population is given by:

$$V(t) = V(0)\left(1 + (t/t_e)\right)^{1/3}$$

where the encounter timescale, t_e, is given in terms of the number of clouds per unit volume, n_C, their average mass, m_C and an impact parameter function $a(\approx 9.8)$ by:

$$t_e = 4V_m^3(0) / \left(3\pi^{3/2} G^2 n_c m_c^2 \ln a\right)$$

The accuracy of such a formula is determined both by the evolution of the disk GMC population, and by the reduction of interaction events when the orbits have diffused sufficiently to take them out of the region of the disk occupied by GMCs for a significant portion of the orbit. Both of these tend to reduce the rate of the diffusion with time. Wielen (1977) examined the diffusion rate by direct observation of populations of various ages in the solar heighbourhood. He found than an equation of similar form to that above gives an adequate description, but with an exponent of 1/2 and an encounter timescale of 5×10^7 years.

As dynamical evolution proceeds, the velocity ellipsoid does not remain spherical, because radial diffusion is more active than axial diffusion. Wielen finds that, for a dynamically old population, the ratio of axial-to-radial velocity dispersions, $\sigma_w : \sigma_v$, tends to 0. 6 : 1.0. With this fact, we can transform the observed line-of-sight velocity differences to a histogram of the vertical velocity dispersion in the LMC, assuming that the PN population is dynamically old, and that the HI is dynamically young. The data implies that σ_T(HI) =9.4 km s^{-1} and σ_T(PN) =37.1 km s^{-1}.

Are the observations consistent with the hypothesis that the increase in velocity dispersion is the result of the operation of the stellar orbital diffusion process? The answer to this requires a knowledge of the age distribution of the precursor stars. We believe that most of the LMC planetaries had initial stellar masses near 0.88 $M_\odot$, but there exists a tail in the distribution extending to about 1.4 - 1.6 $M_\odot$. Typical ages of these stars at the time of PN formation can be estimated from the main-sequence lifetimes given by Iben and Tutukov (1985), assuming that these occupy 90% of the total lifetime of the planetary nebular precursor, and show that the bulk of the PN have an age of near 3.5×10^9 years. Thus, the PN population predates, by a considerable margin, any encounter between the LMC and SMC.

These ages can now be substituted in either the Wielen (1977) or the Spitzer and Schwartzchild (1951, 1953) formulae. The principal uncertainty in the use of these equations is the mass appropriate for the giant HI clouds in the LMC. Using a mass density of 3×10^{-24} g cm^{-3}, the PN age derived above, and the observed velocity dispersions of the HI and the PN population, these imply that the mass of the typical scattering cloud is about 1.6×10^5 $M_\odot$. This should be compared with the value found for Galactic molecular clouds, $1.5 \times 10^5 M_\odot$ (Liszt *et al.*).

Using Wielen's work, with the observed velocity dispersions, and a constant diffusion coefficient of 6.0×10^{-7} (km $s^{-1})^2$ yr^{-1}, the indicative age of the PN population is 2.1×10^9 years. Using his velocity-dependent diffusion formulae gives ages of $(2.5\text{-}3.6) \times 10^9$ years. Both of these figures are sufficiently close to the ages given above to give us confidence that diffusive processes are very similar to those operating in our local region of the Galaxy.

4. References

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