7. THE LMC-SMC-GALAXY SYSTEM

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THE INTERACTING MAGELLANIC SYSTEM

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ABSTRACT. The Magellanic System is viewed focusing on the global interactions in the System. These give insight into its history and structure. The past orbits of the Magellanic Clouds (MCs) are examined. A tidal encounter between the Large and Small Magellanic Clouds (LMC, SMC) has almost certainly occurred within the last 10^9 yrs. This hypothesis is supported by the observed structure of the Magellanic System, and so is accepted. The Magellanic Stream is an indirect result of the tidal encounter which is crucial to understanding the Magellanic System. It is a complex interacting gas feature, bifurcated along its entire length with many anomalous velocity H I clouds alongside. The possible models for the Magellanic Stream are examined and here I propose that its origin is due to the collision of a multi-phase halo with the vast region of gas between the LMC and the SMC. In this respect the polar subsystem around our Galaxy is seen to be particularly important. The popular tidal model for the origin of the Magellanic Stream fails to satisfy key observational features, and is thus rejected.

1. Introduction

The characteristic time for galaxy-galaxy encounters is less than the age of the universe and so interactions between galaxies are important for their evolution. The unusual situation of having a pair of Magellanic galaxies so close to a large spiral like our Galaxy means that there will be interactions in the LMC-SMC-Galaxy system not seen in isolated Magallanic pairs. As the MCs are the only galaxies near our own to have significant amounts of gas, there will also be interactions with any outer halo gaseous component of our Galaxy.

A description of the global dynamics of the Magellanic Systems is needed before features like star formation, chemical evolution and kinematics in the LMC and SMC can be fully understood. Conversely, these features can give information on parameters of the interactions. Thus, the interacting Magellanic System is a key probe into many aspects of our Galaxy, from its mass to its halo environment, as well as being a doorway to understanding the formation and evolution of galaxies in general.

1.1 THE MAGELLANIC SYSTEM

The two MCs are interacting and are physically connected by a common HI envelope (see Fig.1 of Mathewson & Ford 1984). The strongest part of this envelope forms a bridge with embedded stars (Mathewson 1976; Irwin *et al.* 1985) between the LMC and the SMC. This inter-Cloud region (ICR) is extensive; it covers some 600 sq. deg. and contains as much HI as the SMC! The long Magellanic Stream (Mathewson *et al.* 1974) extends in a straight line from the MCs for about 100° and is regarded as an indication of global interaction in the Magellanic System. The Stream is seen only in HI and no stellar component has been found.

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2. The Encounter Event

2.1 COEVAL SIGNS OF INTERACTION

The velocity-distance measurements of Mathewson *et al.* (1988) indicate a short timescale (few x 10^8 yrs) for the splitting of the SMC. This suggests that a recent event like the tidal collision of Murai and Fujimoto (1980) is the cause. This is supported by the discovery of young (age ~10^8 yrs) stars in the inter-Cloud region. The velocity dispersion of the Magellanic Stream suggests an age of not greater than a few x 10^8 yrs (Tanaka 1981; Cohen 1982)—thus the hypothesis is made that these signs of interaction are coeval and point to a recent event.

2.2 ORBITS

The orbits of the MCs have been investigated by many people, mainly with a view to reproducing the Magellanic Stream (Murai & Fujimoto 1980, 1986; Lin & Lynden-Bell 1982; Fujimoto & Sofue 1976; Kunkel 1979; Davies & Wright 1977; Tanaka 1981; Mathewson *et al.* 1987; Wayte 1990). The most extensive orbital examinations (Murai & Fujimoto 1980; Wayte 1990) indicate that a 'collision' between the LMC and SMC within the last 10^9 yrs is likely.

The evolution of the three-body system (LMC-SMC-Galaxy) is examined over the past 10^{10} yrs by integrating back in time for a range of input parameters. Murai and Fujimoto (1980) and Wayte (1990) used different initial conditions and covered different parts of the parameter space. For both sets of integrations, the orbital direction of the barycentre about our Galaxy is taken to be such that the Magellanic Stream is trailing, as originally advocated by Mathewson (1976) and Fujimoto & Sofue (1976). It is consistent with the direction determined by Feitzinger *et al.* (1977) and the direction implied by the compression of the HI contours in the Magellanic System.

Both Murai and Fujimoto (1980) and Wayte (1990) find that a 'collision' of the LMC with the SMC within the last 10^9 yrs is difficult to avoid. Specifically, Wayte finds that for orbits in which the LMC and SMC are bound for 10^{10} yrs, there is about a 50% chance of a 'collision' in which the LMC and SMC centres come within 10 kpc of each other. Murai and Fujimoto (1980) advocate a close collision about 2 x 10^8 yrs ago, while Wayte (1990) advocates an encounter of 5 - 10 kpc about 2 - 7 x 10^8 yrs ago.

The closeness of the 'collision' determines whether it is a purely tidal encounter or whether hydrodynamical effects should be considered. The SMC still has a very high proportion of gas which would not be expected if the SMC passed closer than 5 kpc from the centre of the LMC, given the efficiency of the Spitzer-Baade (1951) process. The distribution of encounter distances within the last 10^9 yrs from Wayte also indicates that the 'collision' was probably greater than about 5 kpc; so, it is a tidal encounter.

2.3 STRUCTURAL FEATURES

For this encounter to be accepted, there must be signs of it in the current structure of the Magellanic System. The first sign is the large depth and velocity spread of the SMC (Mathewson *et al.* 1986, 1988; Hatzidimitriou & Hawkins 1989). This is expected from the modelling of Murai and Fujimoto (1980) and is the best pointer to the recent encounter. Mathewson *et al.* find that this depth and spread points to an event 2 x 10^8 yrs ago. In HI, this velocity spread is seen as a clear split, a split of about 40 km s^{-1} which continues through the bridge and into the LMC south of 30

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Dor. In addition the ICR, which physically links the LMC and SMC, has an uncomplicated velocity field (based on velocity centroids) with 'isovels' approximately parallel to the LMC-SMC line (Mathewson *et al.* 1979). Also, the unbound nature of much of the ICR (which has ~30% of the gas in the entire Magellanic System) points to it's being a young feature. Thus the ICR points to the encounter event as its cause. As expected for a tidal feature, the ICR bridge has stars as well as gas (Mathewson 1976; Irwin *et al.* 1990) and the blue stars seen there are about 10^8 yrs old.

Also, the stellar ring features found around the SMC by Albers *et al.* (1987) and the similar shells around the LMC point to the recent encounter. From the theory of shell galaxies using the merger hypothesis, the time since the shell formed can be calculated. For both LMC and SMC the outermost shells give a time of a few x 10^8 yrs since the encounter — again supporting this event.

Finally, the structure of the ICR can be modelled, in part, rather easily by the tidal encounter between LMC and SMC. Toomre and Toomre (1972) show the tidal features that develop after 2 x 10^8 yrs for a system like the two Clouds. Features like the bridge, the NW extension from the SMC, the main LMC spiral arm and outer loop (features B_1 and C of de Vaucouleurs & Freeman 1972) can be reproduced. However, extension of the ICR toward the Magellanic Stream is not reproduced by the model. The extension of the ICR may be due to the Galaxy's gravity, or to ram pressure on the bridge by gas in the galactic halo, as suggested by the HI contours which bunch up on the leading edge of the MCs and ICR.

3. The Magellanic Stream

The Magellanic Stream also points to the recent encounter. For instance, the Stream is made up of many differenct velocity components in bulk motion (Mirabel 1981; Wayte 1990) and these random motions give a timescale of order 10^8 yrs for doubling the width of the Stream. Other structural aspects of the Stream also give free expansion ages of ~ 10^8 yrs.

Despite the large number of observational characteristics (or perhaps because of them) the origin of the Magellanic Stream has been an unresoved problem since its discovery. For an explanation of its origin, the tidal model was the natural first choice because of the success of Toomre and Toomre (1972) in modelling features in interacting galaxies and because only straightforward familiar physics is used. However, the tidal and other models suffer from deficiencies in explaining some key observational characteristics. The models so far put forward to explain the Stream's origin are:

a) the diffuse ram pressure model
b) the discrete ram pressure model
c) the tidal model
d) the primordial model and
e) the turbulent wake model.

The primordial and turbulent wake models both have some aesthetic features. However, they have too many fundamental difficulties like the abundance of the Stream (Songaila 1981) to be acceptable. The real controversy is between the tidal and ram pressure models. In the 1980s the ram pressure models were produced because of the problems the tidal models had in explaining the observational characteristics of the Stream. The most successful tidal model has been that of Murai and Fujimoto (1980) who were able to obtain the high negative velocities at the tip of the Stream which had eluded earlier investigations. They did not, however, address all the

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observational features of the Stream, and so the tidal model still has some fundamental problems which have to be examined. Indeed, in this regard, Professor Alar Toomre has never published a tidal model of the Stream even though it was discovered when he was very active in the field of tidal interactions.

3.1 THE TIDAL MODEL

The key difference between the tidal and ram pressure models is that in the latter, stars (except for very young blue stars if the gas density is high enough for them to form) are not expected to be in the Stream, whereas in the former, they are. Finding stars in the Stream is all that is needed for the tidal model to reign supreme. However, none have been found, despite searches toward MSI (Brück & Hawkins 1983; Mathewson 1985). This may be reconciled with the tidal model if MSI is 1.6 to 2 times further away than the LMC (i.e. greater than 80 kpc distant); however, the models of Murai and Fujimoto put MSI closer than the LMC.

Other problems with the tidal model include the observed predominantly radial motion (Mathewson *et al.* 1979)— the tidal model requires a significant transverse motion; the overall density gradient and splitting into six velocity distinct clouds — not matched by the tidal models.

A severe problem with the best tidal models (Murai & Fujimoto 1980, 1986) is that one of two unlikely possibilities must be accepted. Initially, Murai and Fujimoto (1980) had the LMC and SMC bound for 10^{10} yrs, but introduced the test particles which produced the Stream only some 2 x 10^9 yrs ago; if introduced 10^{10} yrs ago the test particles would have been scattered all over the place (Murai & Fujimoto 1986). To avoid this difficulty, Murai and Fujimoto relaxed the requirement that the LMC and SMC have been bound for 10^{10} yrs to their having become bound only some 1.7 x 10^9 yrs ago.

In any case, there are tidal forces acting in the Magellanic System and these will be part of any model for the Magellanic Stream — the real question is whether the tidal force is the dominant force for the production of the Stream.

3.2 RAM PRESSURE MODELS

The discrete ram pressure model (Mathewson *et al.* 1987) depends upon the encounter event to produce the inter-Cloud region. Then collisions between the ICR gas and high velocity clouds (HCVs) in the galactic halo produce the Stream. Thus the Stream consists of intermixed HVC and ICR gas. With reasonable assumptions, this model naturally explains the major characteristics of the Magellanic Stream (Mathewson *et al.* 1987). In addition, if the 'halo HVCs' are more confined in their galactocentric distances to say 40-70 kpc then the Magellanic System would sweep up most of these HVCs so that this model would explain aesthetically why there are virtually no halo HVCs in the southern galactic hemisphere. However, there are a few difficulties and uncertainties in this model. Even though there are six concentrations (of approximately equal angular length) in the Stream it is essentially continuous; for this purely discrete model, I would expect there to be breaks in the Stream with the concentrations being of different angular size. The other main difficulty is — are there enough HVCs in the halo to collide with the ICR and produce the Stream?

A significant feature of the ICR is that its HI contours are rather smooth and bunched on the leading edge (nearer the galactic plane), but corrugated and extended in the downstream direction on the trailing side. It is from these corrugated extensions (called fingers) that the Magellanic Stream extends. Another interesting feature of the ICR is that a substantial fraction of it has a 'swiss cheese' appearance. The ICR and Stream are seen superimposed at places in the region of the 'fingers'; also there is a sharp drop in velocity from the ICR to the Magellanic Stream at the

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beginning of the Stream. This indicates that the Magellanic Stream is more than a pure extension of the fingers. The important connection between the ICR and the Stream is that the fingers point in the Stream direction; indeed, two prominent fingers abut the Stream which continues the bifurcation throughout its length.

The ram pressure models are attractive because they can explain observational characteristics, like the density variation along the Stream, which the tidal model leaves unexplained. In addition, the ram pressure models allow the Stream to be formed quickly so that initially unbound orbits of the MCs about our Galaxy are permitted. The main difficulty with the ram pressure models is that the gaseous outer halo environment of our Galaxy has not been directly observed, leaving the question: is all that gas suggested to be in the very outer halo really there? However, Wayte (1990) has given substantial evidence that there are some HVCs and a diffuse corona in the halo. As seen above, there are other difficulties that these ram pressure models face, but they are not as severe as the problems with the other models.

However, both still have some difficulties in matching the observed characteristics of the Magellanic Stream. For instance, the diffuse model does not explain the separation of the Stream into six velocity separate clouds with little transverse motion; while the discrete model does not explain the overall continuous nature of the Stream.

With HVCs and hot coronal gas in the galactic halo it is obvious that the gas in the halo is like the local interstellar medium in that there is more than one phase present. This suggests that a combination of the diffuse and discrete ram pressure might be the origin of the Magellanic Stream. This more realistic, multi-phase medium could quite conceivably produce the velocity separate clouds in an overall continuous Stream with bifurcation. This is the model (the 'Multi-Phase Model') I favour as it can satisfy all the observed characteristics of the Stream. Detailed ram pressure modelling should be done using full hydrodynamic code (not nearly as easy as tidal modelling) to examine this model in detail.

To conclude, I consider the origin of the Magellanic Stream to be due to the effect of the galactic halo environment interacting with the Inter-Cloud Region which has only been around since the recent encounter between the LMC and the SMC some few x 10^8 years ago.

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