The Magellanic System: Stars, Gas, and Galaxies
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Magellanic type galaxies throughout the Universe

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Abstract. The Magellanic Clouds are often characterized as "irregular" galaxies, a term that implies an overall lack of organized structure. While this may be a fitting description of the Small Cloud, the Large Magellanic Cloud, contrary to popular opinion, should not be considered an irregular galaxy. It is characterized by a distinctive morphology of having an offset stellar bar and single spiral arm. Such morphology is relatively common in galaxies of similar mass throughout the local Universe, although explaining the origin of these features has proven challenging. Through a number of recent studies we are beginning to get a better grasp on what it means to be a Magellanic spiral. One key result of these works is that we now recognize that the most unique aspect of the Magellanic Clouds is not their structure, but, rather, their proximity to a larger spiral such as the Milky Way.

Keywords. galaxies: dwarf, galaxies: evolution, galaxies: interactions, Magellanic Clouds, galaxies: structure

1. Introduction

While the Small Magellanic Cloud can properly be thought of as an irregular galaxy, the Large Magellanic Cloud shares a number of key morphological properties with a population of galaxies classified as Barred Magellanic Spirals (SBm). These properties include a stellar bar, the center of which may or may not be coincident with the dynamical center of the galaxy, a single, looping spiral arm, and often a large star-forming complex at one end of the bar. In the broadest of terms, Magellanic spirals are often simply referred to as being "asymmetric" or "lopsided", but they are not "irregular."

The earliest comprehensive look at Magellanic spirals was carried out by de Vaucouleurs & Freeman (1974) who noted the structural similarity between the LMC and a number of other nearby galaxies. Much of the subsequent work was aimed at understanding the origin of the lopsided structure that characterized Magellanic type galaxies. Odewahn (1994) carried out a photographic survey of Magellanic spirals and concluded that the vast majority of them had companions. The implication of this was that interactions were primarily responsible for the asymmetric properties of this class of galaxy. Theoretical work and some simulations could accurately account for the apparent lopsidedness of Magellanic spirals, but not the frequency of them.

Over the past decade or so we have also seen a proliferation of statistically significant samples of galaxies that show that objects sharing the basic properties of Magellanic spirals are common in both the local Universe and at intermediate redshift. It is becoming more and more apparent that the old adage of studying the Magellanic Clouds in order to learn more about the evolution of galaxies in general is quite true. The Clouds are the nearest examples of a broad population of galaxies that contributed and continue to contribute significantly to the global star formation rate and gas content of the Universe as a whole. In this contribution we present the results of a number of recent studies of the properties of other Magellanic spirals. What emerges is both a better understanding of Magellanic-type galaxies throughout the Universe and, perhaps more importantly, a recognition that the most unique aspect of the Magellanic Clouds is not their structure, but their proximity to the Milky Way.

2. In the Local Group

We begin our survey of Magellanic type galaxies throughout the Universe with a look at how the Magellanic Clouds fit into the Local Group. We have heard a great deal at this conference about the stellar content of the Clouds, so the focus here will be on the H I properties of galaxies in the Local Group. A casual glance at the morphological distribution of galaxies in the Local Group quickly reveals one of the most interesting aspects of the Magellanic Clouds. They are the only H I-rich companions of the large spirals, M 31 and the Milky Way; the low mass companions to the large spirals are almost exclusively either dwarf ellipticals or dwarf spheroidals. The LMC is the fourth most massive galaxy, by H I mass, in the Local Group behind only M 31, the Milky Way, and M 33. The Small Magellanic Cloud, on the other hand, is the most gas-rich of any of the Local Group irregulars, surpassing NGC 3109 and IC 10. The rest of the gas rich irregular galaxies tend to lie at large distances from either of the large spirals, suggesting a coarse morphology-density relation exists even in low mass galaxy groups such as our own. It is worth noting here that the distribution and kinematics of H I within the LMC and SMC is not unusual. The H I holes and extended H I distribution we see in the Clouds are also seen in almost every H I-rich galaxy, especially late-type ones, observed. In addition, galaxies with the H I mass of the Magellanic Clouds ($10^8 - 10^9$ $M_\odot$) represent the plurality of galaxies in similar groups. Freeland, Stilp, & Wilcots (2009) derived the H I mass function of galaxy groups shown in Figure 1. While the numbers are small, it is clear that mass function is relatively flat at low and intermediate masses; there is nothing uncommon about either the H I mass or the distribution of H I in the Magellanic Clouds.

Much attention has also been given to the Magellanic Stream, but it is interesting to note that M 33 and M 31 appear to be connected by an H I bridge of similar mass (Braun & Thilker 2004). While this tells us more about the complex dynamical history of the Local Group than it does about the Magellanic Clouds, it is yet another bit of evidence to show that the properties of the Magellanic Clouds (and Magellanic Stream) are reflective of conditions common within the local Universe. Indeed, the Magellanic Clouds are important because they are not uncommon objects, but rather are outstanding nearby examples of more distant objects.

3. A statistical approach

We can see how the Magellanic Clouds fit into the larger picture of the population of galaxies by making use of a number of different surveys of star-forming and gas-rich galaxies in the nearby Universe and at higher redshifts. We have already seen that the H I masses of the Clouds place them on the flat part of the H I mass function, slightly less massive than an $M_\star$ galaxy. H I mass functions, however, sample only the local Universe and, therefore, are not necessarily representative of the population of galaxies at intermediate and high redshift. We might ask the extent to which the Magellanic Clouds have counterparts in the more distant Universe. One population of interest is that of the luminous compact blue galaxies (LCBGs) which host a large fraction of the star formation at intermediate redshifts. In a study of the H I and optical properties of LCBGs, Garland *et al.* (2004) showed that 30% of the local counterparts to LCBGs are

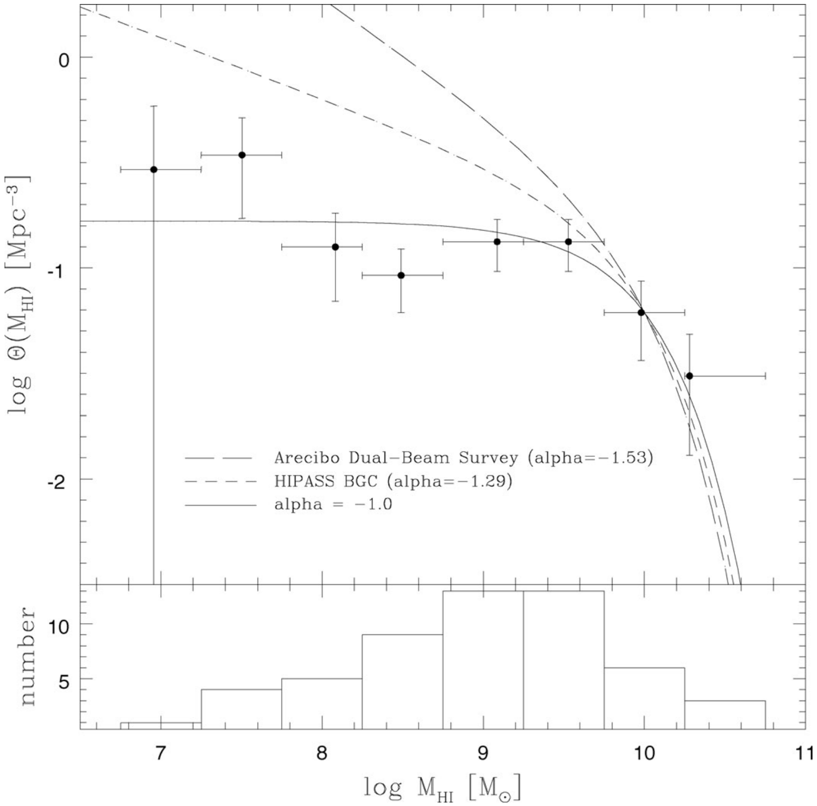

Figure 1. The H I mass function of galaxy groups similar to the Local Group (Freeland *et al.* 2009). The Magellanic Clouds reside on the flat part of the HIMF, somewhat less massive than an $M_\star$ galaxy. The comparison of the H I mass function shows that galaxies with masses similar to those of the LMC and SMC are common in the group environment

Magellanic type spirals and massive irregulars. This is consistent with the findings of Wolf *et al.* (2007) who showed that galaxies with masses similar to the Magellanic Clouds make up an increasingly large fraction of the star-forming galaxies at intermediate redshifts. In addition, galaxies like the LMC make up a strong plurality of the galactic contribution to the total H I density of the Universe and the total cross-section of the damped Lyα systems (Ryan-Weber *et al.* 2003). In the context of this presentation, these examples only serve to demonstrate that galaxies with the mass and luminosity of the Magellanic Clouds are common throughout the Universe and, as such, are important tracers of the overall evolution of the population of galaxies.

4. Magellanic type galaxies as companions

One of the themes to emerge from the body of work on Magellanic-type galaxies throughout the Universe is that the LMC and SMC are unique only in the fact that they are companions of significantly larger disk galaxies. Of the 75 Magellanic-type galaxies included in Odewahn (1994)'s survey, none are companions to a large spiral. Fundamentally this means that an ongoing encounter with a larger galaxy is not required to explain the morphological properties of Magellanic type galaxies. The intermediate H I mass galaxies in other groups are broadly distributed within the group and are not preferentially companions to the larger galaxies (Freeland *et al.* 2009). We can turn this argument around and ask how the Magellanic Clouds compare to the companions of other spirals. James, O'Neill, & Shane (2008) surveyed the star formation characteristics of the companions to 53 spiral galaxies. Of those 53 galaxies, only 9 had companions, and the LMC would be the most luminous of all of them. Zaritsky *et al.* (1997) also found that the LMC is among the brightest of all of the companions in their sample of disk galaxies. Comparing the Milky Way to a specific similar spiral, Pisano & Wilcots (2000) identified two H I-rich companions to NGC 6946, both of which were less massive than the Magellanic Clouds. SPH simulations reach a similar conclusion; Libeskind *et al.* (2007) found that companions of comparable luminosity and mass to the LMC were quite rare in the SPH simulations of galaxy and structure formation. Simply put, the Magellanic Clouds are not typical satellite galaxies; they are more luminous and more massive. At the same time the Magellanic Clouds are unique among galaxies of their type in the fact that they do reside in close proximity to a large galaxy.

5. Morphological characteristics of Magellanic spirals

What truly distinguishes Magellanic type galaxies from other classes is their characteristic optical morphology. Broadly speaking, Magellanic galaxies contain an optically visible stellar bar that is typically displaced from the apparent center of the galaxy. In fact, for most Magellanic type galaxies (and, indeed, late-type spirals in general) it is difficult to determine where the center of the galaxy actually resides. For example, while NGC 925 is not quite a Magellanic, it is a late type spiral for which the dynamical center as defined by the H I velocity field, the optical center of the bar, and the optical center of the outer isophotes do not coincide (Pisano, Wilcots, & Elmegreen 2000). For the LMC the dynamical center derived from carbon stars is not coincident with the dynamical center derived from H I observations (van der Marel *et al.* 2002). True Magellanic spirals such as the LMC often display a one-armed spiral morphology. An optical image of IC 1727 in Figure 2 shows this quite nicely, and NGC 3664 and NGC 4618 are other excellent examples of the characteristic bar and one-armed spiral morphology (Wilcots, Lehman, & Miller 1996).

In what was the first detailed review of the properties of Magellanic type galaxies, de Vaucouleurs & Freeman (1974) described a class of objects that, contrary to popular opinion, had a distinct morphology characterized by this strong optical asymmetry. Asymmetry, however, appears to run rampant amongst all disk galaxies. Approximately half of all spirals have asymmetric H I profiles (Richter & Sancisi 1994; Baldwin, Lynden-Bell, & Sancisi 1980) and this fraction increases to 75% for late-type spirals (Matthews, van Driel, & Gallagher 1998). Lopsidedness extends to the stellar distribution as well and Rix & Zaritsky (1995) found that nearly 30% of all spirals have asymmetric stellar distributions.

The prevalence of asymmetry among disk galaxies naturally led to a broad search for a cause. Baldwin *et al.* (1980) suggested that differential precession of the disks might account for the widespread observed lopsidedness. The short timescales of this process, however, are difficult to reconcile with the prevalence of assymmetry. Interactions are more commonly identified as the cause of asymmetry in disk galaxies. Walker, Mihos, & Hernquist (1996) and Zaritsky & Rix (1997) both suggest that minor mergers could be responsible. Simulations show that the accretion of a small companion of $\sim 10\%$ of the mass of the primary can lead to a strongly asymmetric disk that persists for a few dynamical times (Walker *et al.* 1996). Using a combination of excess blue luminosity in lopsided galaxies and a quantitative measurement of the Fourier amplitudes of the asymmetry, Zaritsky & Rix (1997) derived an upper limit on the current rate of accretion of companions among field galaxies. Rudnick, Rix, & Kennicutt (2000) showed a similar

Figure 2. A V-band image of the classic Barred Magellanic spiral, IC 1727, showing the one-armed morphology and stellar bar.

correlation between lopsidedness and recent star formation that suggested that minor mergers might be the cause of both. In an analysis of photographic plates Odewahn (1994) suggested that essentially all Magellanic spiral type galaxies had companions, further leading credence to the notion that interactions were to blame for asymmetry. Wilcots *et al.* 1996) looked at the H I properties of a small sample of Magellanic spirals and suggested that minor mergers and accretion could be connected to the observed lopsidedness.

Interactions, and even minor mergers, are short-lived phenomena and the simulations indicate that the resulting asymmetry should only last for $\sim 10^9$ years (e.g., Walker *et al.* 1996) — too short to account for the prevalence of lopsidedness. A more compelling model was proposed by Levine & Sparke (1998) and Noordermeer, Sparke, & Levine (2001) that simply shows that a disk offset from the dynamical center of a dominant halo can result in long-lived asymmetry that is consistent with the observed velocity fields of lopsided late-type spirals. In other words, once a disk starts offset from the dynamical center, it is likely to remain offset. The observable effects of the Noordermeer *et al.* (2001) models include a velocity field in which the curvature of the isovelocity contours on the receding and approaching sides are different to the extent that one side of the rotation curve appears to have turned over while the other side continues to rise. The magnitude of the effect is a function of the fraction of the total mass in the disk, how far the disk is displaced from the dynamical center, and whether or not the disk orbits in a retrograde sense. Few true Magellanic spirals have been observed in enough detail to see the extent to which these models reflect reality.

Wilcots & Prescott (2004) took a systematic look at asymmetry in Magellanic type spirals by surveying the H I properties of a sample of 13 such galaxies. They found that only four of the 13 had actual companions, in stark contrast to the Odewahn (1994) study. In addition, the ongoing interactions are all quite weak and unlikely to do much to alter the morphology or dynamics of the primary galaxy. Most interestingly, the H I profiles of the Magellanic spirals with companions were no more or less asymmetric than the H I profiles of the galaxies that did not have a companion. Lastly, the H I profiles of the Magellanic spirals — a sample selected because of their optical asymmetry — were no more or less asymmetric than the H I profiles of typical galaxies in the field. It is extremely unlikely that current, or even recent, interactions have much to do with the optical asymmetry prevalent amongst Magellanic-type galaxies. Whatever the initial cause of lopsidedness amongst Magellanic spirals, it is clear that the asymmetry is long-lived and it is manifested largely in the stellar distribution but not so evident in the H I profiles or rotation curves.

6. Case study: NGC 4618 and NGC 4625

Up to this point we have concentrated on the properties of Magellanic spirals as a class of galaxy. The next step in building our understanding of Magellanic-type galaxies throughout the Universe is to investigate the detailed astrophysics of a small sample of such galaxies. NGC 4618 and NGC 4625 are probably the best nearby examples of Magellanic spirals outside of the Local Group and the targets of detailed study using both radio and optical techniques.

6.1. *The effects of interactions*

Both NGC 4618 and NGC 4625 are classified as Magellanic-type galaxies, they are interacting with one another, and are connected by a distinct H I bridge (Bush & Wilcots 2004). They are, in other words, very similar to the Magellanic Clouds, with the major exception that NGC 4618 and NGC 4625 are not companions to a larger galaxy. Bush & Wilcots (2004) calculated that the interaction began some 0.2–0.7 Gyr ago and, to date, has had little effect on the structure of the participating galaxies. The H I profiles and rotation curves of both galaxies remain remarkably symmetric, further raising doubts about the connection between interactions and the characteristic asymmetry of Magellanic-type galaxies.

The fact remains that a number of the most prominent Magellanic spirals such as the LMC and NGC 4618 *are* interacting. The effects of these interactions on the morphology and kinematics of the gas and stars in the galaxies involved are simply not well understood. There is obviously a wide range of variables that go into understanding the effect of a close passage between two galaxies on their morphologies. These include: the mass ratio of the galaxies, the fraction of the total mass in the disk, and the orientation of the interaction (retrograde vs. prograde). Bush & Wilcots (2004) completed a *VLA* study of the NGC 4618-NGC 4625 pair and their results show that one of the galaxies (NGC 4625) has a disk that accounts for only 6% of the total mass while the other (NGC 4618) has a disk that accounts for 45% of the total mass. This may be one the keys to understanding the effects of an interaction on Magellanic spirals. NGC 4618, the galaxy with a higher fraction of its mass in its disk, has suffered more tidal disruption than its more massive companion, NGC 4625, which apparently has a higher fraction of its mass in its halo. Whether or not the NGC 4618-NGC 4625 pair is characteristic of the class of Magellanic-type galaxies as a whole has yet to be seen.

Many of the ongoing interactions in which Magellanic-type galaxies are participating more typically symptomatic of minor mergers (Wilcots & Prescott 2004). NGC 4288 and

NGC 4861 are two excellent examples of this phenomenon. In both cases the smaller companion has less than 10% of the mass of the Magellanic-spiral and there is some suggestion that such accretion events are more reflective of the continuing growth of the individual galaxies (e.g., Wilcots *et al.* 1996).

6.2. *Stellar kinematics of a Magellanic spiral*

As one might expect, the only Magellanic spiral for which we have a good understanding of its internal structure and dynamics is the LMC. Van der Marel *et al.* (2002) used the kinematics of the carbon stars to measure the internal structure and stellar velocity dispersion of the LMC. Among other results, they found that the velocity dispersion of ~ 20 km s^{-1} implies that the disk of the LMC is remarkably thick. Whether these are unique properties of the LMC or more characteristics of the population of Magellanic spirals as a whole has yet to be determined and resolution of this particular issues requires a new suite of observations of other Magellanic-type galaxies. We have initiated just such a survey of the stellar kinematics of a sample of Magellanic spirals beginning with NGC 4618.

Because of its favorable inclination and relative proximity, NGC 4618 is probably the best Magellanic spiral beyond the LMC itself in which to study the structure and kinematics of these galaxies. Prescott *et al.* (in preparation) used the Sparsepak integral field unit (Bershady *et al.* 2005) and the bench spectrograph on the *WIYN* 3.5m telescope to measure the stellar kinematics in NGC 4618. The distribution of the Sparsepak fibers on NGC 4618 is shown in Figure 3 and we show the spectrum extracted from one of the central fibers in Figure 4. Information about the stellar kinematics was extracted using the cross-correlation of the observed spectrum of NGC 4618 with a series of stellar templates, and an example of the cross-correlation is shown in Figure 5.

Based on the analysis of the Mg I stellar absorption lines, Prescott *et al.* (in preparation) find the stellar velocity dispersion perpendicular to the disk to be ~ 23 km s^{-1}, comparable with the value found in the LMC. There is some variation of the velocity dispersion with radius; particularly, the velocity dispersion is 50% higher in the bar than it is in the rest of the disk. Assuming a scale height of ~300 pc, the disk mass is roughly 30% of the total dynamical mass of NGC 4618.

7. Are the bars real?

One of the enduring mysteries surrounding Magellanic-type galaxies is the nature of their stellar bars. Abraham & Merrifield (2000) found that the bar fraction decreases from early type spirals to Sc, but then *increases* for even later type disk galaxies. In other words, extreme late-type spirals are more likely to be barred than Sc-types. Noguchi (2001) saw a curious enhancement in his "concentration parameter" for extreme late-type galaxies, again suggesting that these galaxies are more likely to host central stellar concentrations like bars than Sc type galaxies. Perhaps one explanation is that an initially offset disk is more likely to be unstable to bar formation (Junqueira & Combes 1997). Even if extreme late-type galaxies are more susceptible to the formation of bars, it is not clear that the bars in Magellanic sprials are dynamically similar to those in earlier type galaxies. Strong stellar bars typically manifest themselves as S-shaped isovelocity contours in the observed velocity field of barred galaxies. The velocity field of NGC 4618, however, does not have that characteristic S-shape (Prescott *et al.*, in preparation); in short, the bar seems to be having only a modest effect on the gas kinematics in the central part of the galaxy. A similar situation is seen in IC 1727, another barred Magellanic spiral.

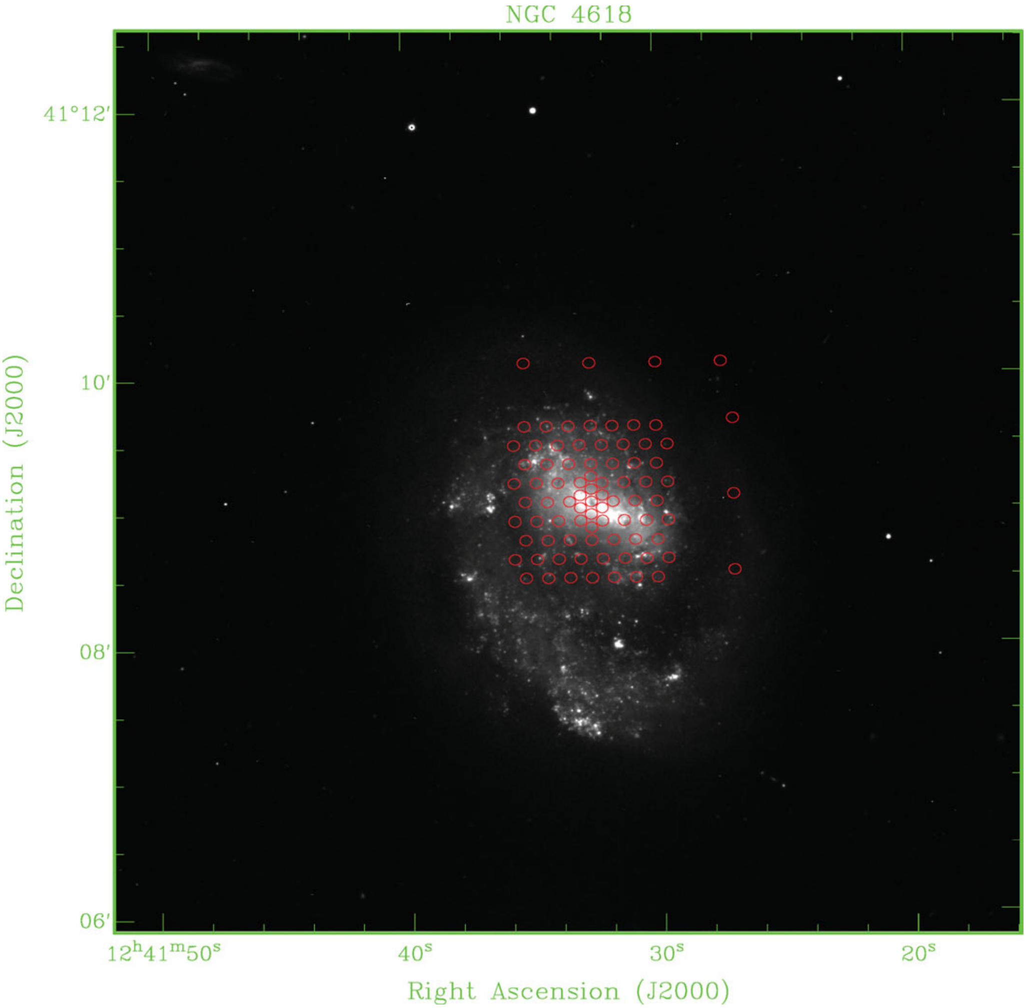

Figure 3. The small circles represent the individual Sparsepak fibers overlayed on an B-band image of NGC 4618.

While there has yet to be a true systematic study of the properties of bars in Magellanic type galaxies, the data obtained to date suggest that these bars are not "real."

8. Where do we go from here?

We have seen that the study of Magellanic-type galaxies now includes detailed observations of the structure and dynamics of a number of individual objects. In addition we now have surveys of other Magellanic-type galaxies at a range of wavelengths. What do we learn from these studies? First, the morphology and the kinematics of the Magellanic Clouds are not unique. The LMC and SMC are, very clearly, simply nearby examples of a population of galaxies that is well represented throughout the Universe. Second, Magellanic-type galaxies are not nearly as asymmetric or lopsided as they seem, particulary as measured by their H I profiles. Third, given the absence of evidence that interactions have played a large role in shaping the morphology of Magellanic spirals, we are still searching for a broadly applicable model for the origin of the asymmetry so

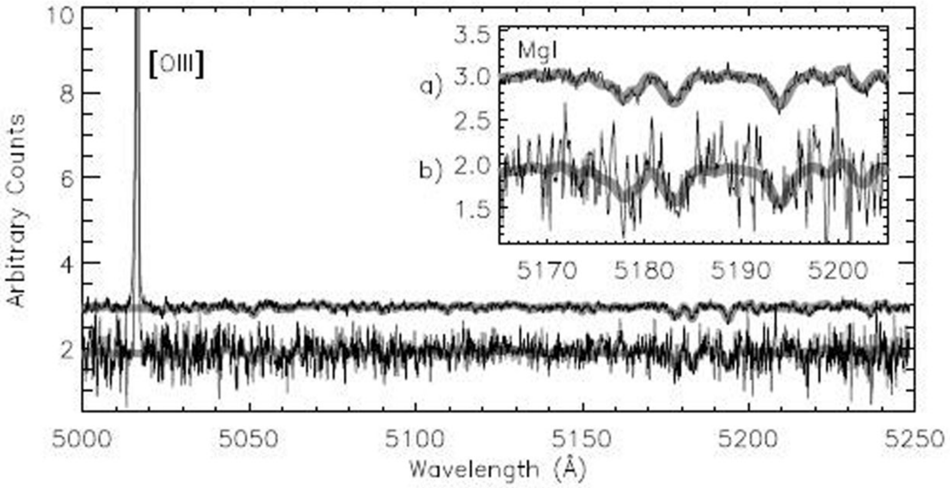

Figure 4. The spectrum of NGC 4618 extracted from one of the central Sparsepak fibers. The inset specifically shows the Mg I lines which formed the basis of much of the analysis.

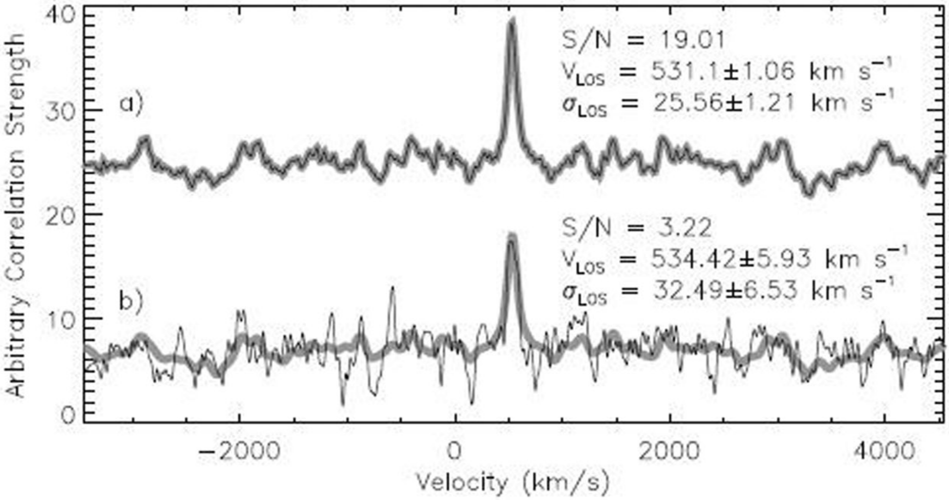

Figure 5. This figures shows the results of the cross-correlation of the observed spectrum of NGC 4618 with the spectrum of a stellar template. The centroid of the cross-correlation peak is the line of sight velocity while the width corresponds to the velocity dispersion in the galaxy.

common in these galaxies. Lastly, one can conclude that it is their proximity to the Milky Way that distinguishes the Magellanic Clouds from other similar galaxies.

Despite a number of significant advances in our understanding of Magellanic-type galaxies over the past few years, there remain a handful of key areas in which our ability to put the LMC and SMC in a proper context is limited. The first is the question of whether the bars in Magellanic spirals are "real." In the few cases studied to date there is little compelling kinematical data to suggest that the bars are "real." This is particularly the case with NGC 4618 Prescott *et al.* (in preparation) and IC 1727 as we have shown here. Clearly, we need more kinematical data for both the stars and gas on a much larger

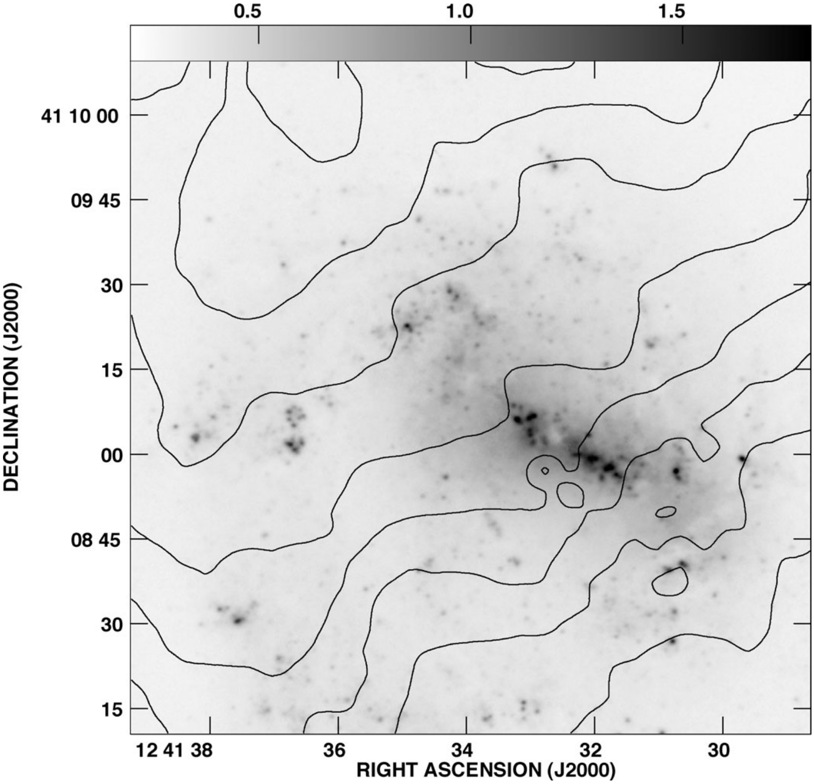

Figure 6. This is a comparison of the H I velocity field overlayed on an optical image of the SBm galaxy NGC 4618. The isovelocity contours show little evidence that the bar is strongly affecting the gas kinematics in the central part of the galaxy.

sample of Magellanic spirals. The obvious question would be that if bars in Magellanic spirals are not “real”, then what are they?

Second on the list would be a better understanding of the impact of minor mergers on the structure and internal dynamics of late-type spirals. Wilcots & Prescott (2004) found that some Magellanic spirals do have small companions. We simply do not know what the effect of a minor merger might be on such late-type galaxies, especially if their disks are already off-set.

The third key area is to better understand the frequency with which Magellanic-type galaxies are found in other groups and what their place in those groups might be. This requires moderately deep and wide-field observations of a statistically significant sample of groups. We are in the midst of such a survey of the H I properties of galaxy groups and one example (GH 98) of the results is shown in the figure below. The contours correspond to the H I column density and they are overlayed over an image of the group obtained with the *WIYN* 0.9m telescope. Not surprisingly we find that groups are the sites of a number of interactions; in fact almost all of the H I detected galaxies are interacting (Freeland *et al.* 2009). Two important properties emerge from this work: it is not uncommon to find that H I galaxies are still ”falling into” galaxy groups (i.e. groups are still growing) and that structures like the Magellanic stream are also not uncommon. Perhaps studying the Magellanic Clouds not only allows us to learn more about the evolution of galaxies, but also the evolution of galaxy groups. Given that our understanding of the origin of the Magellanic Clouds themselves continues to evolve, the future of the study of

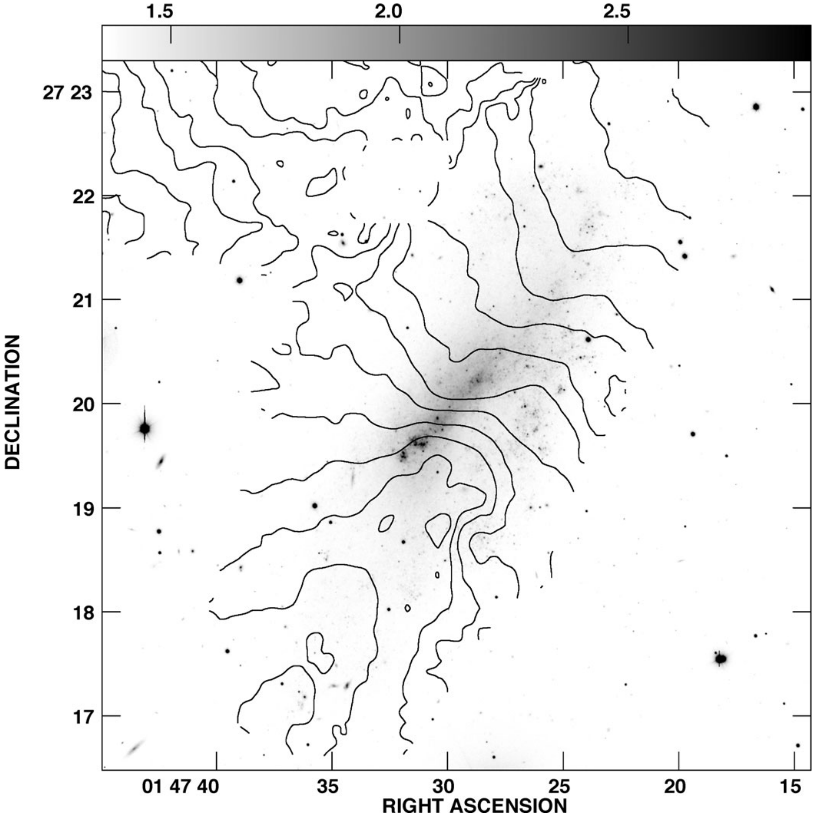

Figure 7. This is a comparison of the H I velocity field overlayed on an optical image of the central part of the SBm galaxy, IC 1727. While there is some evidence of streaming motions, the velocity field does not show the characteristic "S-shaped" isovelocity contours seen in strongly barred galaxies. The contours to the north and east of IC 1727 are the outer isovelocity contours of its companion NGC 672.

Magellanic-type galaxies throughout the Universe will likely focus on this aspect of their evolution. In other words the question is: what does the Magellanic system tell us about the evolution of the Local Group and what does the dynamical evolution of other galaxy groups tell us about the origin of the Magellanic Clouds?

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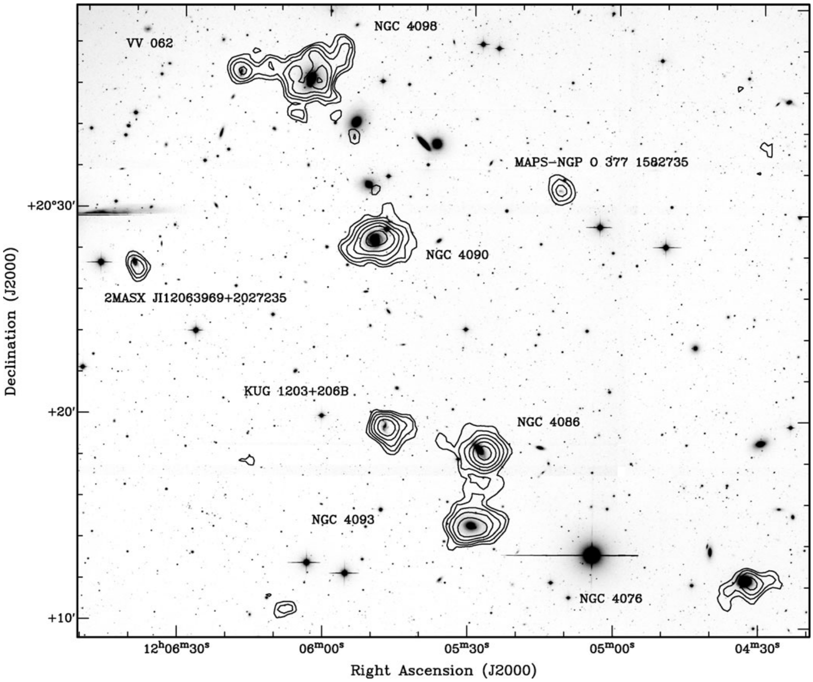

Figure 8. The contours represent the H I column density map overlayed on an R band image of the GH 98 galaxy group (Freeland, Stilp, & Wilcots 2009. Nearly all of the H I detections show clear signs of interactions and at least one pair of galaxies is connected with an H I bridge. This is an example of an environment in which the accretion of galaxies into the group continues in the present epoch.

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