Neutral Gas in the ISM of Nearby Galaxies

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ABSTRACT

This paper covers the past decade of neutral gas measurements of spiral and dwarf irregular galaxies for which an explosion of measurements have been made. These measurements of neutral gas provide an important context for the interpretation of Spitzer Observations. The phases, properties and methods of measurement of the neutral ISM are presented. The quantity and distribution of neutral ISM in nearby galaxies is reviewed. The atomic component is present in all spirals and dwarf irregulars but the molecular gas fraction varies significantly being lowest in dwarf irregulars and low surface brightness galaxies. The distribution of molecular gas in spirals also varies with equal numbers of galaxies with central concentrations and holes. The effects of stars on the ISM, in particular their creation of photodissociation regions (PDRs), is reviewed. I note the over abundance of star formation rate studies in the literature and challenge this community to think "green" and start researching the recycling aspect of ISM evolution by measuring all the sources and sinks of ISM in galaxies.

Subject headings: galaxies: ISM — infrared: galaxies — infrared: ISM — ISM: gas — ISM: structure

1. Introduction

This review paper on the neutral ISM gas in galaxies provides context for the many results of observations with the Spitzer Space Telescope (Werner et al. 2004) reported at this conference. There has been an explosion of results in this field due to the advent of millimeter wave interferometers mapping CO in the galaxies and the improvements to existing centimeter wave interferometers mapping HI. A new wave of galaxy CO and HI surveys has been prompted in response to the need to interpret Spitzer data. The remainder

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of this paper covers the following: phases and properties of the neutral ISM, distribution and quantity of the neutral ISM in nearby galaxies, the effects of stars on the ISM, and the lifeycle of ISM gas.

2. Phases and Properties of Neutral ISM

The phases of the neutral medium are stable ISM gas states of density and temperatures in a pressure equilibrium or virial equilibrium and their properties are summarized in Table 1. The warm intercloud gas is a mixture of neutral and ionized diffuse media. The cold neutral medium is a cooled and condensed gas in pressure balance with the intercloud gas. The giant molecular clouds are, in general, confined by self-gravity and hence are denser than the CNM. Photodissociation regions are essentially giant molecular clouds irradiated by nearby starlight and thus have densities comparable to GMCs, but are heated to much warmer temperatures by the photoelectrically ejected electrons from dust grains. Our abilitiy to detect the neutral ISM of any galaxy is limited by what we can detect with its tracers (see Table 1). If the tracer has limitations, and they all do, than our measurement with that tracer provides an incomplete measurement, typically a lower limit.

The structure of the warm neutral medium in nearby galaxies, e.g. the Large Magellanic Cloud (LMC, Fig. 1, Kim et al. 2003), is fractal with a k^{-3} power spectrum that is quite similar to that found in the Milky Way (MW). Similar processes such as turbulent motions instigated by supernova explosions, must be present in all galaxies to shape the WNM into froth. The structure of the CNM is harder to assess because it is observed with the HI 21 cm line absorption towards background quasars. However, the absorption appears to be stronger towards higher column density of HI 21 cm emission in the SMC (Dickey et al.

Table 1. Phases of the Neutral Gas

Phase	tracer	density [cm^{-3}]	temperature [K]
warm intercloud gas			
warm neutral medium (WNM)	HI 21 cm emission	0.1	8000
warm ionized medium (WIM)	Hα , [CII]158 μm	0.1	8000
cold neutral medium (CNM)	HI 21 cm absorption	>10	80
giant molecular clouds (GMCs)	^{12}CO lines	>3000	4 - 80
photodissociation regions (PDRs)	[CII]158 μm, rotational H_2	>3000	100-1000

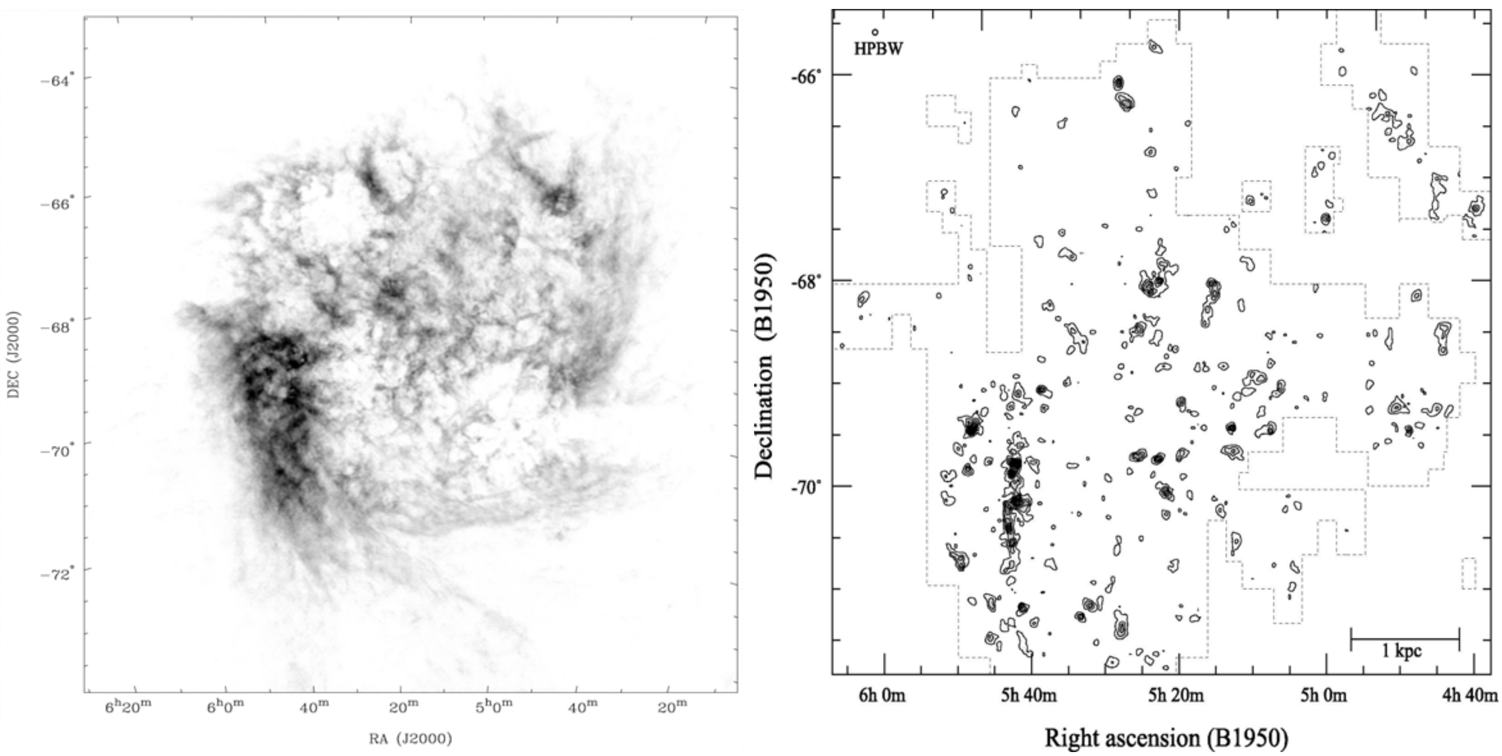

Fig. 1.— The integrated intensity of HI 21 cm of the Large Magellanic Cloud which traces the WNM (left, Kim et al. 1999) and the integrated CO J=1-0 intensity which traces the GMCs (right, Fukui et al. 1999).

2000) suggesting that the CNM can condense when the density of WNM reaches a threshold. The molecular clouds also coincide with peaks of HI atomic column densities and appear more like individual clouds than a larger structure. Indeed, many of the molecular clouds are self-gravitating and virial masses can be derived from the line widths (ΔV) of the CO rotational transitions and the sizes of the CO emission maps (R):

$$\Delta V = (GM/R)^{\frac{1}{2}}$$

Thus the structure of these giant molecular clouds (GMCs) can be desribed by a mass spectrum. The mass spectrum of the giant molecular clouds in the LMC has a power law of $\sim$-1.5 which is similar to that found in the MW (Mizuno et al. 2001) suggesting a similar formation process.

Virial analysis of clouds is difficult for more distant galaxies due to angular resolution limitations and most work simply uses the X-factor to derive molecular masses directly from the CO J=1-0 line transition luminosity:

$$L_{CO} = T_{CO} \Delta V \pi R^2$$

. Assuming the GMCs are in virial equilibrium, the CO luminosity and cloud mass are related as

$$L_{CO} = (3G\pi/4\rho)^{\frac{1}{2}} T_{CO} M.$$

The X-factor for the Milky Way is known to within a factor of 2 with 3.6×10^{20} cm^{-2} (K km/s)$^{-1}$ reported by Scoville et al. (1987) based on a correlation of the CO brightness and virial mass of MW GMCs and 2.3×10^{20} cm^{-2} (K km/s)$^{-1}$ reported by Strong et al. (1988) based on gamma ray and CO intensity measurements. The MW X-factor has been applied to other galaxies; however, it can change with galaxy properties, especially under different metallicities (Fig. 2, Mizuno et al. 2001). The X-factor has been derived to be 9×10^{20} cm^{-2} (K km/s)$^{-1}$ for the LMC (Fukui et al. 1999) and $1 - 5 \times 10^{21}$ cm^{-2} (K km/s)$^{-1}$ for the SMC (Mizuno et al. 2001). Recent comparison of the Spitzer/MIPS dust emission to the gas components in the ISM of the LMC suggests that the X-factor for the LMC may in fact be closer to the MW values (Bernard et al. 2008).

3. Quantity and Distribution of Neutral ISM in Galaxies

Nearby galaxies offer the best opportunity to investigate the quantity and distribution of the neutral ISM gas components via maps of the HI 21 cm line emission and the CO J=1-0 and J=2-1 line emissions.

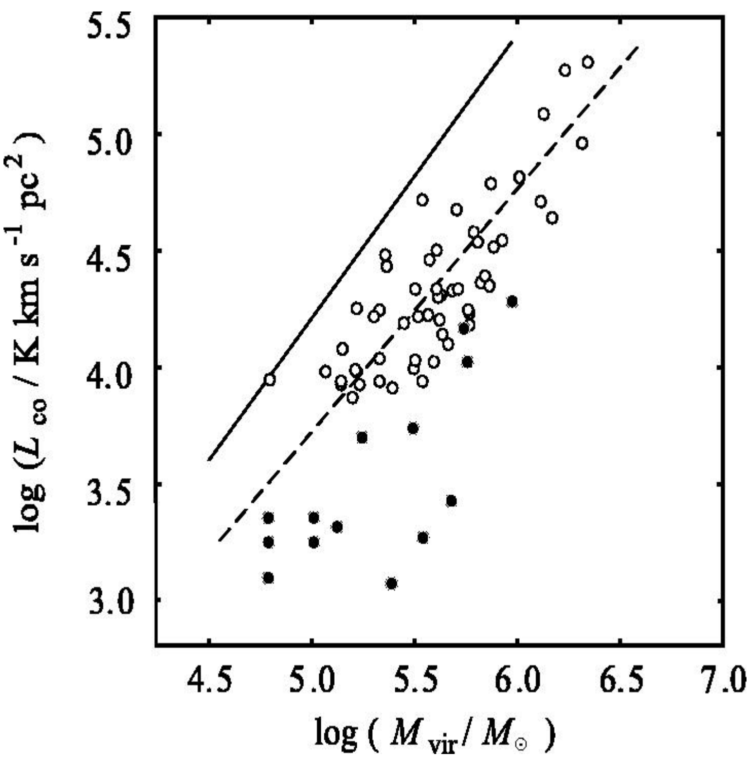

Fig. 2.— The derivation of the X-factor for GMCs in the LMC and SMC and their comparison to the MW value (Mizuno et al. 2001).

The quantity of gas in different phases of the ISM appears to vary with different galaxy environments. Table 2 outlines the gas masses in the different phases of ISM in the nearest, well observed galaxies. These nearby galaxy gas distributions require large scale mapping strategies of HI and CO J=1-0 and several have only recently been published. The LMC has only one tenth the neutral atomic gas mass as the MW. Half of this atomic gas resides in the cold neutral medium, which is the largest fraction of CNM in any nearby galaxy. The molecular gas mass is only one tenth of the atomic gas in the LMC which is a much smaller fraction than found in the MW. However, the usual gas tracers for the ISM gas matter are missing at least half the ISM mass in the galaxy as evidenced by the total ISM matter estimates by Bernard et al. (2008; see also this proceedings) from the MIPS 160 μm images of the LMC (Meixner et al. 2006). This matter is most likely neutral and perhaps most likely cold atomic gas but molecular gas without CO emission cannot be ruled out. Thus the MIPS 160 μm measurements of galaxies may be providing us the best total measurement of ISM matter in nearby galaxies. Estimates of ISM matter using similar techniques as Bernard et al. (2008) in nearby galaxies would be useful to determine if similar missing ISM matter issues exist in other galaxies. The SMC has a similar quantity of atomic neutral gas as the LMC, but the molecular gas mass is only one hundredth that of the atomic component. Submillimeter continuum observations of select molecular clouds in the SMC also indicate a significant fraction of "missing" ISM gas matter (Bot et al. 2007). Thus it appears for smaller mass, dwarf irregular galaxies, the ISM gas content decreases and the fraction of the gas in the molecular form decreases even more dramatically. However, while dwarf irregular galaxies have smaller absolute masses of ISM than large spirals like the MW, the fraction of ISM mass to total galaxy mass is higher. Indeed, statistical studies of large samples of dwarf irregular galaxies show that the gas mass fraction increases dramatically at lower total mass of galaxies (Geha et al. 2006). Nevertheless, the ISM gas mass is almost totally atomic, with very few detections of molecular gas, e.g. 4×10^6 $M_\odot$ for IC 10 (Leroy et al. 2006), and upper limits of 10^3 - 10^5 $M_\odot$ of molecular gas in others (Buyle et al. 2006).

The ISM gas content of galaxies not only varies with type of galaxy (spiral vs. dwarf irregular) but also within the class of large spiral galaxies. The HI atomic gas mass of the five spiral galaxies, MW, M31, M51, M81 and M51, are the same within a factor of two and all above 10^9 $M_\odot$. However the molecular gas content, as traced by CO, varies by a factor of $\sim$1000, with the MW and M51 containing almost half of its ISM gas mass in the molecular form, and M81 containing an almost undetectable fraction. Investigations of 15 low surface brightness, spiral galaxies by Matthews et al. (2005) finds few detections in CO with corresponding molecular gas masses of $(3.3-9.8)\times 10^6$ $M_\odot$, similar to that found in the Magellanic Clouds and dwarf irregulars. The reasons for these dramatic variations cannot be explained by metallicity differences and indicates a fundamental aspect of molecular cloud

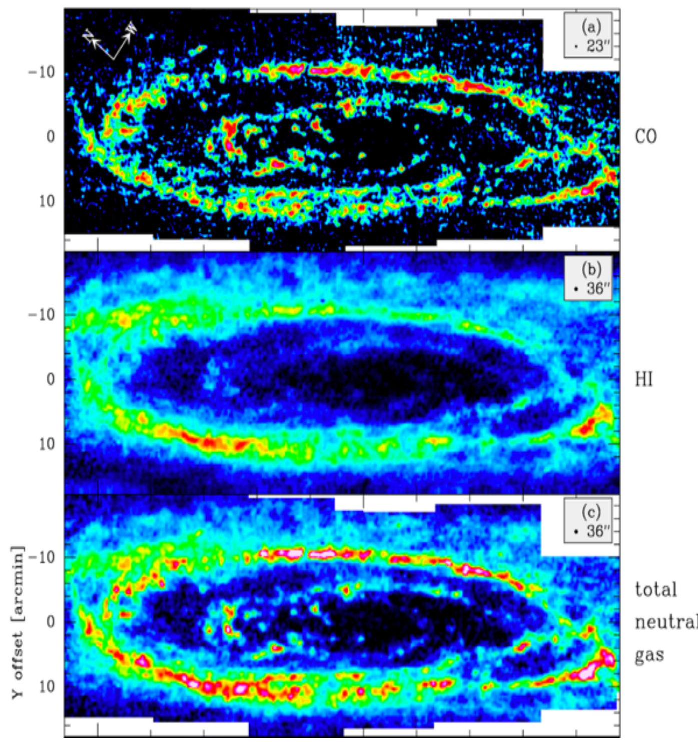

Fig. 3.— M31, the Andromeda Galaxy, in the CO J=1-0 line emission (top; Nieten et al. 2006), HI 21 cm line emission middle (Brinks & Shane 1984) and the combined (H_2(CO)+HI), total neutral gas map (Nieten et al. 2006).

formation and galaxy environment or total mass of the galaxy.

The location of the ISM in nearby galaxies also shows a variety as well. The spiral galaxies have been given a lot of attention because of the current interest in understanding star formation in nearby galaxies. In a CO J=1-0 imaging survey of 20 nearby spirals by Sakamoto et al. (1999), nuclear concentrations of the molecular gas were common; however, the sample was biased towards those galaxies previously selected in CO single dish surveys. In a slightly more unbiased survey of nearby galaxies (SONG) in the CO J=1-0 line (Helfer et al. 2003), Regan et al. (2001) finds that half of galaxies are centrally peaked and the other half are not. In the grand designed spirals such as M51 and NGC 6949, the CO emission appears to correlate well with the optically bright stellar population, many of which have bright central peaks. However, in galaxies with equally bright but probably more evolved stellar bulges, e.g. NGC 7331 (Regan et al. 2001) and M31 (Nieten et al. 2006), the CO emission is absent from the galaxy center where the stellar light is brightest. In the galaxies that do have central peaks, there is excess CO emission above an extrapolation of an exponential fit to the CO disk emission; an effect that is comparable to the stellar light in bulge above the norm of the disk; i.e. a CO bulge exists too (Regan et al. 2006). While the CO emission and stellar population do not always correlate, the CO and 8 μm PAH emission do always correlate in the SONG galaxies suggesting the 8 μm Spitzer/IRAC images trace the ISM gas content of galaxies well (Regan et al. 2006). Interestingly, the CO emission appears to be centrally located in the galaxies with faint CO emission, e.g. M81 (Casasola et al. 2007) and low surface brightness galaxies (Matthews et al. 2005); however, this may be a selection effect of the observations given the limited sample.

The location of the WNM, as traced by HI 21 cm emission, with respect to the molecular gas component, as traced by CO, can be coincident or anti-correlated with both relations appearing in one galaxy. For galaxies with relatively faint CO emission, e.g. LMC (Figure 1) and M81 (Casasola et al. 2007), the CO emission, in general, coincides with peaks in the HI 21 cm emission images with a few CO clouds associated with a dearth of HI emission. In the larger spirals in which CO emission is quite bright relative to the HI emission, the CO emission in the outer regions of the galaxy disk are coindicent with the peaks of HI emission. However, in the inner regions, there is often a molecular gas ring with very little HI gas (e.g. M31, Figure 3) or even a central CO bulge (e.g. M51, Schuster et al. 2007). In general, the atomic gas is much more extended radially and in disk thickness and appears diffuse compared to the molecular gas. This change suggests a radial variation of molecular cloud formation. At even larger radial distances, high velocities clouds are detectable around M31 in HI (Westermeier et al. 2005) with the improved sensitivites now possible with cm wave radio telescopes. These high velocity clouds appear to be similar to those found around the MW and are evidence of continued gas infall and outflow in normal galaxies. The HI Nearby

Galaxy Survey (THINGS) will provide a more uniform census of the location and mass of HI in galaxies (Walter et al. 2008).

Most of the current work in the literature analyze the molecular gas in comparison to the atomic gas. However, the future efforts in this area will be combining the molecular and atomic gas components into total neutral gas maps such as Crosthwaite & Turner (2007) did for NGC 6949. These combined neutral gas maps convert the CO line emission into a hydrogen column density image using an adopted X-factor and adds it to the hydrogen atom column density derived from the HI 21 cm emission. A surface mass density map is derived with corrections for inclination and the heavier elements ($\times 1.36$) included. The interest in making such maps is driven by star formation studies which require knowledge of the total gas reservoir to calculate star formation efficiencies. Thus in the future, we can expect more papers combining such surveys as SONG and THINGS to derive total ISM gas reservoirs. To these efforts, we make a cautionary note that the MIPS 160 μm emission may provide the most sensitive probe of the total mass and surface density of ISM gas from which stars are born.

4. Effects of Stars on the ISM

Stars, in particular massive stars, have three impacts on the ISM in galaxies: star formation, radiative effects and mechanical energy effects. Star formation depletes the ISM and a lot of research, reported elsewhere at this conference, has been done to measure the star formation rates in galaxies. For example, the LMC has a star formation rate of 0.1 $M_{\odot}$ yr^{-1} based on the recent discovery of $\sim$1000 young stellar objects (YSOs) in the LMC (Whitney et al. 2008). Dividing the total gas mass of the LMC by this rate suggests a 10 Gyr lifetime for the remaining ISM gas. However, such a simple calculation brushes over the complicated physics involved in determining the process of star formation. The star formation rates in galaxies appear to increase with gas mass surface density in the so-called Schmidt/Kennicutt (1989) law. Wong & Blitz (2002) find that the star formation rate correlates better with the molecular gas surface density than with the total gas mass density or atomic gas mass density. These new findings indicate that the rate limiting step in the star formation process may be the conversion of the atomic into the molecular gas, which then turns into stars at a predictable rate.

The radiation of the young massive stars photodissociates their natal molecular clouds creating photodissociation regions (PDRs) at their surfaces. The [CII] 158 μm line emission is one of the dominant cooling lines of PDRs. In a study of some giant molecular clouds in M31, Rodriguez-Fernandez et al. (2006) finds that the [CII] 158 μm correlates spatially best with the Spitzer/MIPS 24 μm emission and Hα and appears sometime adjacent to and sometimes coincident with the CO J=1-0 emission and HI 21 cm emission. Comparison of the [CII] line emission to the total FIR flux indicates a 2% heating efficiency in converting the massive star radiation into heating of the PDR gas. A tight correlation between [CII] and CO emission is found for starburst galaxies (Stacey et al. 1991) and many have suggested using the [CII] line as a star formation tracer. However, the [CII] 158 μm line can also come from the WNM and the WIM. For example, in the LMC, Kim & Reach (2002) estimate that at least 20% of the [CII] emission measured in the LMC arises from the WNM and up to 46% in the WIM.

Systematic studies of PDRs in 60 nearby, normal galaxies was possible with ISO in a key program (PI: Helou). The WNM and PDRs revealed a range in physical conditions: heating efficiencies of 0.01-0.1%, gas densities of 10^2- $10^{4.5}$ cm^{-3}, and incident radiation fields of 10^2- $10^{4.5}$ G_0 (Malhotra et a. 2001). This large sample revealed an unpredicted correlation of gas density and incident radiation (G_0) which can be plausibly explained as a pressure from the HII regions, photoinized by the same stars, expanding into the neighboring PDRs (Malhotra et al. 2001). The Spitzer/SINGS project (PI: Kennicutt) investigated this same sample of nearby galaxies measuring the warm rotationally excited H_2 lines of S(0) 28.2 μm and S(1) 17 μm. Analysis of these lines indicates that the PDR gas temperatures range from $\sim$100-1000 K, they comprise 1 to 30% of the total H_2 gas mass and the intensity of these H_2 rotational lines correlates well with the PAH emission strength supporting the suggestion of their origin in PDRs (Roussel et al. 2007).

Studies of mechanical energy feedback of massive stars via stellar winds and supernovae has been less systematically studied in nearby galaxies. The porous structure of the ISM provides suggestive evidence that these holes in the HI gas distributions may have been evacuated by such feedback (e.g. Kim et al. 1999 for the LMC). However, a more direct link between the massive star population and the energy of the feedback required for the structure formation remains absent for many cases making such claims speculative.

5. The life cycle of ISM gas

Most of the literature has concentrated on the consumption aspect of the ISM evolution, i.e. star formation. However, the evolution of the ISM in galaxies involves a larger life cycle of physical processes including star formation, the ISM processes and the stellar mass-loss enrichment of the ISM. As a community, we need to think more "green" and consider the whole life cycle of the ISM and in particular on the recycling aspects of the ISM's evolution. In our legacy project entitled, Spitzer Survey of the Large Magellanic Cloud: Surveying the

Table 2. Quantity of the Neutral Gas in Some Nearby Galaxies

Galaxy	HI Mass [$M_\odot$]	CNM HI fraction	H_2 Mass [$M_\odot$]	M^X	Refs.
LMC	5.2×10^8	0.5	4.2×10^7	5.6×10^8	1, 2, 3, 4
SMC	4.6×10^8	0.1	4.2×10^6	...	5, 3, 6
MW	4.8×10^9	0.31	5×10^9	...	7, 3,8
M31	5.1×10^9	0.32	3.6×10^8	...	9, 3, 10
M51	2.9×10^9	...	2×10^9	...	11, 12
M81	2×10^9	...	4.2×10^6	...	13, 14

References. — [1]Kim et al. (2003), [2]Fukui et al. (2001), [3] Dickey et al. (2000), [4]Bernard et al. (2008), [5]Stanimirovic et al. (1999), [6]Mizuno et al. (2001), [7]Kulkarni & Heiles (1987), [8]Scoville & Sanders (1987), [9]Brinks & Shane (1984), [10]Neiten et al. (2006), [11]Rots et al. (1990), [12]Schuster et al. (2007), [13] derived from data in Allen et al. (1997), [14] Casasola et al. (2007)

Table 3. Sources & Sinks for ISM Gas in Galaxies

Sources:
Existing gas of galaxy
Asymptotic Giant Branch (AGB) star mass loss
planetary nebulae enrichment
massive star dusty mass loss
supernovae
novae
infall gas from intergalactic medium
Sinks:
star formation
galactic winds/outflows
tidal stripping

Agents of a Galaxy's Evolution (SAGE), we are studying three key transition points of the evolving ISM: the physical processes of the ISM, the formation of new stars and the stellar mass-loss return to the ISM (Meixner et al. 2006). Spitzer's instruments are sensitive to the dust emission which is present in these three transition points. Analysis of this dust emission traces the mass in the ISM, the rate at which it is consumed by star formation and the return of enriched matter from the evolved stellar mass loss. Our goal is to understand the sources and sinks of baryonic matter in the LMC. As a challenge to ourselves, we should strive to measure the physical quantities outlined in Table 3 for all nearby galaxies. Such measurements will provide a much more comprehensive view of the evolving ISM in galaxies.

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