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Atomic and Molecular Gas in Galaxies:

Nearby Dwarfs, Spirals, Early-types, Starbursts

Molecular Gas, Dust, and Star Formation in Galaxies
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Molecular gas and dust in spiral galaxies

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Abstract. Several recent surveys (HERACLES, NGLS, KINGFISH, VNGS) have provided us with sensitive high-resolution observations of the molecular gas and dust content in spiral galaxies within 25 Mpc. I review recent results on the molecular gas content and its relation to star formation, as well as on the gas to dust ratio and the dust heating in spiral galaxies. I also present new results on the effect of environment on the molecular gas content of spiral galaxies.

Keywords. galaxies: ISM — galaxies: spiral

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1. Introduction

One of the major reasons that astronomers are interested in studying molecular gas in galaxies is that it is the molecular gas that provides the primary fuel for star formation. Star formation is a major factor in driving both the evolution of galaxies and how they appear at the present time. Understanding how the molecular gas content, kinematics, and distribution affect the process of star formation is also important for realistic models of galaxy formation and evolution in cosmological simulations.

Over the past 5 years, there has been incredible progress in our ability to measure the molecular gas content in galaxies. This progress has largely been driven by technology, namely the development of spectral line receiver arrays for large millimeter telescopes such as IRAM and the JCMT. These heterodyne arrays have made it possible to map the large angular extents and relatively weak emission of nearby normal galaxies with good sensitivity, calibration, and pointing uniformity (e.g. Leroy *et al.* 2009,Wilson *et al.* 2012).

The availability of higher quality data on the molecular gas content (e.g. Fig. 1). has allowed astronomers to revisit the relationship between gas content and star formation known as the Schmidt-Kennicutt law. Interestingly, there remains significant disagreement over the slope of the power law relation between molecular or total gas content and the star formation rate. For example, Kennicutt *et al.* (2007) analyzed the star formation properties and gas content of individual star forming complexes in the nearby spiral galaxy M51. Expressing the Schmidt-Kennicutt law in terms of surface densities,

$$\Sigma_{SFR} \propto \Sigma_{H_2}^n$$

they found a slope of $n = 1.4$. In contrast, Bigiel *et al.* (2008) performed a similar analysis on a small sample of nearby spirals, including M51, and find a slope much closer to $n = 1$. Obviously both slopes have uncertainties associated with them, and so we might ask whether it matters whether the slope is 1 or 1.4 or perhaps an average of the two. However, the values of the slope measured in these and similar studies fall precisely in the important regime where small differences in the slope *do* matter. A slope of unity reflects a mode of star formation which is a purely linear process (more gas = more stars), while a slope substantially above unity reflects a non-linear mode of star formation (more gas = many more stars).

Similar progress has been made in studying the dust content of nearby galaxies using data from first the Spitzer Space Telescope and more recently the Herschel Space Observatory. The huge improvement in resolution and sensitivity over the past 25 years is readily apparent simply by comparing the ground-breaking maps of M31 at 100 μm from the IRAS satellite (Walterbos & Schwering 1987) with images at the same wavelength obtained with *Herschel* (Smith *et al.* 2012). Sensitive, high resolution maps of the dust emission can be combined with simple models to measure the dust temperature and surface density, while more detailed modeling can provide more details about the composition of the dust and the sources of dust heating (e.g. Draine 2003). The gas and dust data can be combined to measure the gas-to-dust mass ratio and its variations with environmental effects such as metallicity (Muñoz-Mateos *et al.* 2009). These analyses hold out the tantalizing prospect of using continuum observations of the dust emission as an alternative method to measure the total gas content. Such a technique would be especially useful in studying galaxies at moderate to high redshifts (Eales *et al.* 2010, Scoville, this volume), as continuum data can be significantly more sensitive per unit mass than direct observations of the gas content.

2. Measuring molecular gas and dust in galaxies

2.1. *Molecular gas*

Most molecular hydrogen in normal galaxies is cold ($T = 10 - 50$ K) and resides in moderately dense regions ($n = 10^2 - 10^6$ cm^{-3}). Under these conditions, H_2 cannot be observed directly, as temperatures of $\sim$ 200 K are needed to excite the $J = 2 - 0$ transition significantly. As a result, the most common way to measure molecular gas is to observe CO, which is the second most abundant molecule under these conditions. Its $J = 1 - 0$ transition is easily excited via collisions with H_2 for temperatures > 5 K. The CO lines are relatively strong and bright and CO is abundant enough that the lower J lines are usually optically thick. The H_2 column density can be calculated from the

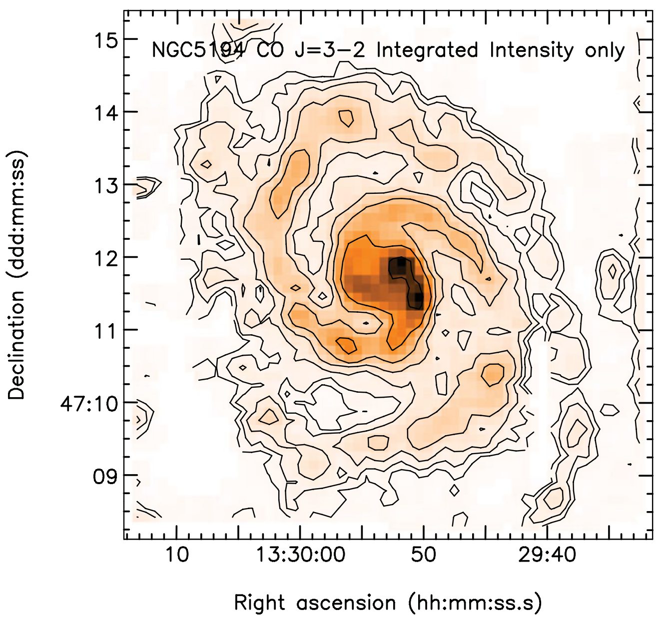

Figure 1. Map of the CO J=3-2 emission in the spiral galaxy M51 from Wilson *et al.* (2012).

intensity of the CO $J = 1 - 0$ line via the CO-to-H_2 conversion factor,

$$N(H_2) = X_{CO} I_{CO}.$$

A commonly adopted value for X_{CO} in galaxies with roughly solar metallicities and typical rates of star formation is $X_{CO} = 2 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ (Strong *et al.* 1988). However, CO emission is notoriously difficult to detect in galaxies with oxygen abundances $12 + \log(O/H) < 8.0$ (Taylor *et al.* 1998, Schruba *et al.* 2012). Although many regions with low metallicity (typically dwarf galaxies and the outskirts of spiral galaxies) may well have lower gas surface densities, another complication is the variation of X_{CO} with metallicity (e.g. Wilson 1995, Bolatto *et al.* 2008, Leroy *et al.* 2011).

2.2. *Dust*

Dust grains in galaxies can occur in a variety of compositions, including silicate grains, carbonaceous grains, amorphous carbon, and polycyclic aromatic hydrocarbons (PAHs), and sizes ranging from a few tens of molecules up to a micron. By mass, dust typically comprises 0.7-1% of the interstellar medium in a galaxy like the Milky Way. A population of dust grains with temperature T_D produces a blackbody spectrum modified by the dust emissivity, κ_λ. If the dust grains all have the same temperature and composition, then the dust mass can be calculated from the flux using, e.g.

$$M_{dust} = 74,220 S_{880} D_L^2 (\exp(17/T_D) - 1)/\kappa_{880}$$

where S_{880} is the 880 μm flux in Jy and D_L is the luminosity distance in Mpc (e.g. Wilson *et al.* 2008). However, the dust in a galaxy is more realistically modelled as having a range of temperatures, while the dust emissivity (and its dependence on wavelength or frequency) are the subject of considerable debate (e.g. Henning *et al.* 1995). Draine (2003) describes a more physically-motivated model including a range of dust sizes, compositions, intensity of the heating radiation field, fraction of heating coming from photon dominated regions driven by young massive stars, etc. The total dust masses obtained

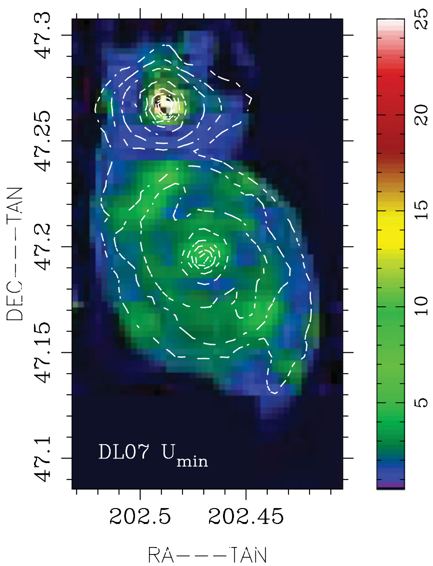

Figure 2. Map of the intensity of the radiation field heating the majority of the dust in M51. Dashed contours indicate the stellar mass density. From Mentuch Cooper *et al.* (2012). Reproduced by permission of the AAS.

using this model and a simple modified black-body function agree to within a factor of two in M51 (Mentuch Cooper *et al.* 2012).

3. Molecular gas in spiral galaxies

Molecular gas in spiral galaxies typically follows an exponential profile with a scale length of around $0.2r_{25}$ (Schruba *et al.* 2011), where r_{25} is the radius of the galaxy at an optical surface brightness of 25 mag per square arcsec. The velocity dispersions measured using the CO $J = 3-2$ line are significantly smaller than the velocity dispersion for the atomic gas and average 7 km s^{-1} outside the very central regions (Wilson *et al.* 2011). Plots of the star formation rate surface density versus the total gas surface density show clear differences between H_2 and HI dominated regions and therefore variations with radius (Bigiel *et al.* 2008).

The star formation "efficiency", SFE, in external galaxies is generally calculated as $SFE = SFR/M_{gas}$ where M_{gas} can be purely atomic, purely molecular, or the sum of both components. Leroy *et al.* (2008) investigated the SFE relative to the molecular gas using the HERACLES survey and compared it to a variety of models invoked to regulate star formation. The analysis suggests that $SFE(H_2)$ does not vary with galactocentric radius, H_2 surface density, stellar surface density, midplane gas pressure, or orbital timescale, and in fact is remarkably constant at a value of 5×10^{-10} yr^{-1}. This analysis implies an instantaneous molecular gas depletion time (given by $1/SFE$) of 2 Gyr. Similar results for the gas depletion time are found from the JCMT Nearby Galaxies Legacy Survey (NGLS) (Wilson *et al.* 2009, Warren *et al.* 2010) and the CARMA STING survey (Rahman *et al.* 2012).

3.1. *The effect of environment on molecular gas content*

There is surprisingly little information available on the effect of large scale environment (group/cluster) on the molecular gas content of galaxies. This is in strong contrast to the wealth of information available on the stellar and atomic gas content and arises primarily from the difficulty in amassing large sensitive CO surveys of nearby galaxies.

Kenney & Young (1989) were the first to search for the effect of environment on the molecular gas content. They compared the CO emission in a sample of spirals in the Virgo cluster divided into an HI-deficient and an HI-normal sample and found that the CO spatial distributions of HI-deficient galaxies was similar to the HI-normal sample. In contrast, a more recent study by Fumagalli & Gavazzi (2008) found that cluster members that are moderately deficient in HI also have a reduced H_2 content. Also relevant here is recent work on the dust content of cluster galaxies by Cortese *et al.* (2010, 2012) which shows evidence for dust depletion in galaxies that are HI-deficient.

The JCMT NGLS was partly selected to address this question of the effect of environment on the molecular gas and dust content. The NGLS is an HI-flux selected sample of galaxies with distances < 25 Mpc and optical diameters $D_{25} < 5'$ covering the full range of galactic morphologies and including both Virgo cluster member and field galaxies (Wilson *et al.* 2012). After the initial sample selection, the field sample was further divided into isolated galaxies and galaxies which are member of groups using group identifications from Garcia *et al.* (1993) and Garcia (1993).

An analysis of the spiral galaxies in the NGLS reveals significant differences in the CO detection rate of the isolated galaxy sample compared to galaxies in groups and the Virgo cluster. Only 15^{+15}_{-5}% of the isolated galaxies in the NGLS are detected in CO, compared to 38 ± 13% for the group galaxies and 62 ± 13% for the Virgo cluster galaxies. In all environments, the galaxies which are detected in CO tend to have larger disk sizes and higher

K-band luminosities (Wilson, Golding *et al.*, in prep.). This environmental comparison suggests that having galaxy neighbors may be important for converting atomic gas into molecular gas and driving star formation which can ultimately build the stellar disk. For example, a recent study of galaxies in voids finds that these galaxies tend to be (atomic) gas rich, have blue optical colors, and relatively low luminosities (Kreckel *et al.* 2012). However, one uncertainty in this analysis is that the mean metallicity of many galaxies in the NGLS is not known. If the isolated NGLS galaxies have below average metallicities, this would both make it more difficult to detect CO emission and would mean that any H_2 masses derived from the CO detections would tend to be underestimated.

4. Dust in spiral galaxies

Foyle *et al.* (2012) have used *Herschel* data to create resolved images of the dust temperature and dust mass surface density in M83 (Fig. 3). They have examined the correlation of the dust surface density and temperature with the molecular gas surface density and the star formation rate. The dust surface density correlates very well with the molecular gas surface density, consistent with a constant gas to dust mass ratio. Interestingly, the dust temperature does not correlate particularly well with the local star formation rate surface density, while the dust mass surface density does.

One interesting question concerning dust in spiral galaxies is when and how the dust-to-gas mass ratio varies from the canonical value of 0.7-1% measured in the Milky Way. Muñoz-Mateos *et al.* (2009) combined Spitzer data from the SINGS survey with available HI and CO data to measure radial profiles of the dust-to-gas ratio. They find that the measurements are consistent with a dust to gas mass ratio that varies linearly with metallicity. Foyle *et al.* (2012) and Mentuch Cooper *et al.* (2012) have examined the dust-to-gas mass ratio using *Herschel* data to carry out a pixel-by-pixel analysis over the inner disk of M83 and M51. Neither galaxy shows strong variations in the dust-to-gas mass ratio, although there is a hint of a radial gradient in M51, consistent with its metallicity gradient (Mentuch Cooper *et al.* 2012).

Another interesting question concerns the primary source of heating for the dust grains. Bendo *et al.* (2010, 2012) have examined the correlation between far-infrared colors observed with *Herschel* and tracers of recent star formation and of the general stellar

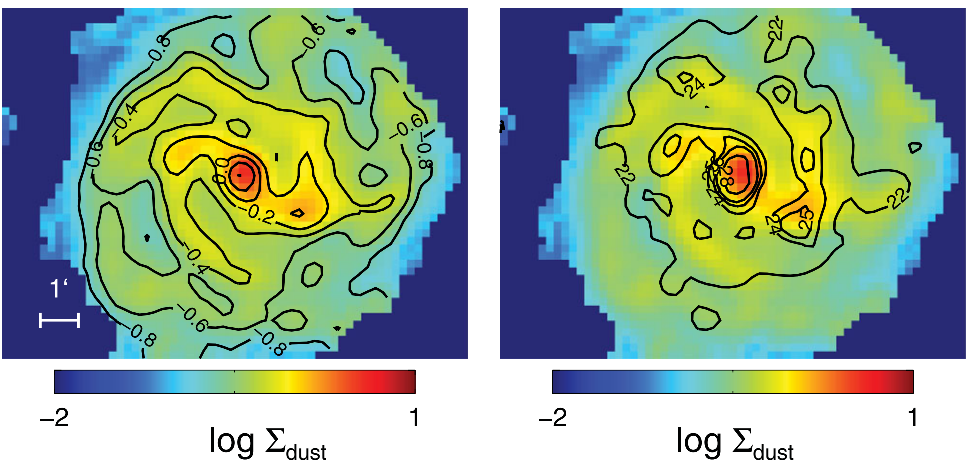

Figure 3. Maps of the dust temperature and mass surface density for the starburst spiral galaxy M83. From Foyle *et al.* (2012).

radiation field in three nearby spiral galaxies (M81, M83, and NGC 2403). They find that the shorter wavelength emission at 70 μm is most strongly affected by local dust heating due to recent star formation, as it shows more pronounced azimuthal variations and a stronger correlation with star formation tracers (Fig. 4). However, emission at longer wavelengths (160 to 500 μm) shows primarily radial trends, which strongly suggests that these longer wavelengths are tracing dust heated by the general interstellar radiation field, including more evolved stars in the disk and the bulge. A similar conclusion that much of the dust was heated by the general interstellar radiation field was drawn from the IRAS maps of M31 (Walterbos & Schwering 1987); only the higher resolution maps of *Herschel* have allowed this study to be extended to more distant galaxies. One interesting aspect of this analysis is that the three galaxies are morphologically very different: M81 is an early-type spiral with a very prominent bulge and relatively little star formation; M83 has a starburst in the center and an H_2-dominated interstellar medium throughout the inner disk; and NGC 2403 is a low-mass late-type spiral where atomic gas is the dominant mass component.

The KINGFISH survey (Kennicutt *et al.* 2011) is a *Herschel* survey of 61 galaxies in the nearby universe. These data can be combined with Spitzer data to generate a complete spectral energy distribution from 3 to 500 μm. Dale *et al.* (2012) measured global spectral energy distributions for the entire KINGFISH sample. The results show a distinct evolution of the dust SED that is correlated with the star formation rate. The general

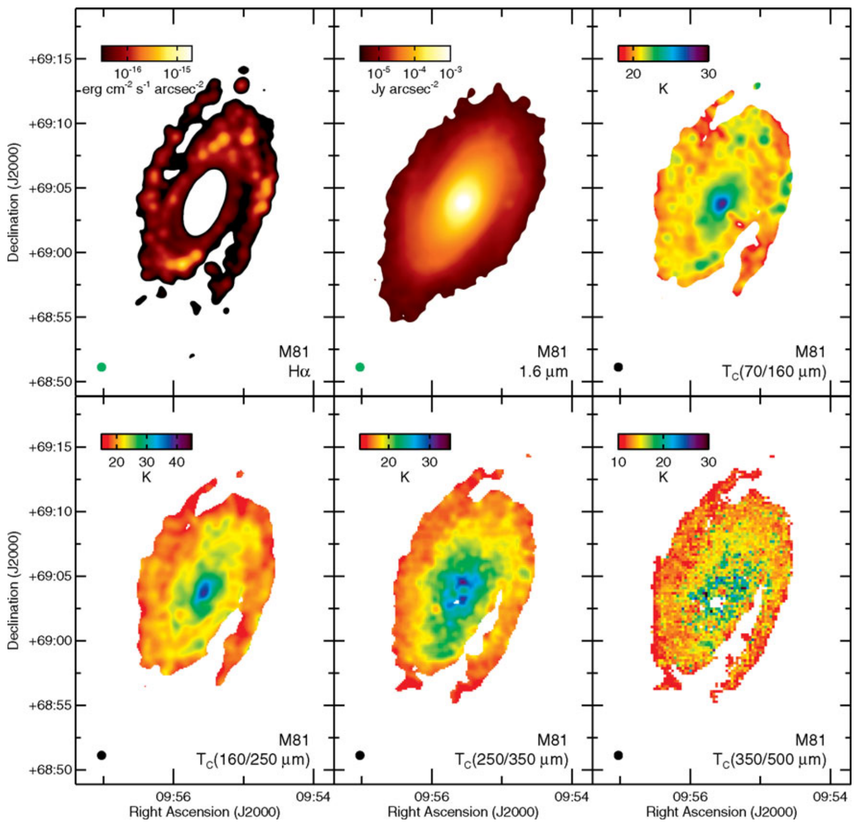

Figure 4. Far-infrared colors of M81 observed with *Herschel*. The H_α and 1.6 μm images are also shown for comparison. From Bendo *et al.* (2012).

trend is for galaxies with higher star formation rates to have higher total luminosities and spectral energy distributions that peak at somewhat shorter wavelengths.

5. Future prospects

Many of the surveys of molecular gas and dust in nearby galaxies are relatively recent and both the analysis and the data collection continue to be in progress. For example, the original HERACLES survey of CO $J = 2-1$ emission from 18 galaxies has been extended to cover 48 galaxies (Leroy *et al.* 2012). Although the CO $J = 3-2$ data for the NGLS are complete, observations are underway for 100 spiral galaxies from the NGLS at 850 and 450 μm using SCUBA-2 . Work is also proceeding to combine data from the NGLS and HERACLES with CO $J = 1-0$ data from Kuno *et al.* (2007) and new ^{13}CO observations to measure physical properties such as the density and temperature of the molecular gas (Rosolowsky *et al.*, in prep.). Both the VNGS and KINGFISH contain significant spectroscopic components, including complete spectra from 200 to 600 μm and targeted observations of far-infrared fine structure lines such as [CII], [OI], and [NII], and the analysis of these data is still in its early phases.

The Atacama Large Millimeter/Submillimeter Array (ALMA) will provide a very powerful tool for studying the molecular gas and dust content of nearby galaxies at spatial resolutions substantially better than can be achieved with even the largest single-dish telescopes. When fully completed in 2012, ALMA will routinely provide images of nearby galaxies on scales a few parsecs to a few tens of parsecs, sufficient to probe the properties of individual giant molecular clouds. Even with its Science Verification data, ALMA has already produced stunning images of the molecular gas in nearby galaxies such as M100 (NGC 4321, Fig. 5) in the Virgo cluster and Centaurus A (NGC 5128), the nearest elliptical galaxy. Indeed, the first refereed paper to be published using ALMA data was a study of a nearby galaxy, the merger system known as the Antennae (Herrera *et al.* 2012).

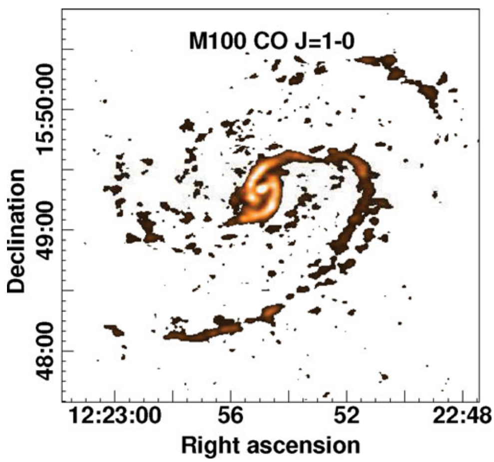

Figure 5. ALMA Science Verification image of the CO J=1-0 emission in the spiral galaxy M100 in the Virgo Cluster. This image is made from the following ALMA data: ADS/JAO.ALMA#2011.0.00004.SV. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ.

With the exploitation of the existing large surveys and new data coming from ALMA, the next several years should see major progress in our understanding of the physical properties of the molecular gas and dust in nearby galaxies and how these properties relate to and affect the star formation process.

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