Presented at the conference "Gas and Galaxy Evolution", held 21 - 24 May 2000 at Socorro, NM, on the occasion of the 20th anniversary of the Very Large Array, eds. J.E. Hibbard, M.P. Rupen, & J.H. van Gorkom. astro-ph/0103025

COLD MOLECULAR GAS, PDRS, AND THE ORIGIN OF HI IN GALAXIES

Ronald J. Allen

Space Telescope Science Institute 3700 San Martin Drive, Baltimore, MD 21218

''It's B stars, stupid!''

Abstract. In the currently-accepted model for star formation out of the interstellar gas in galaxies, the basic construction material is assumed to be large clouds of atomic hydrogen (HI). These clouds are thought to form higher-density complexes of gas and dust, and turn molecular (2). Stars then form out of this molecular gas.

In this paper arguments are advanced for a contrary view, in which the basic construction material is cold molecular gas out of which the stars form directly. HI appears in the region when the leftover 2 is illuminated with UV photons from nearby young stars. The physics of photodissociation regions provides a natural and quantitative explanation for the appearance of HI envelopes around the clouds, and for CO(1-0) emission from the higher-density parts of their surfaces. In this picture, much of the HI in a galaxy is a product of the star formation process, not a precursor to it.

Key words: molecular processes - galaxies: ISM - stars: early-type - ISM: atoms - ISM: molecules

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1. INTRODUCTION

This conference is mainly concerned with the results of observing HI in galaxies, a subject which owes its advancement to the great strides we have made in radiometers and radio telescopes since the first detections in the early-1950s. These advances have included the development of large filled apertures such as the NRAO 300-foot telescope and the Arecibo Observatory, and especially the great synthesis-imaging instruments of the world, the Westerbork Synthesis Radio Telescope and the Very Large Array.

We have been mapping galaxies in HI at ever-increasing resolution and sensitivity for nearly 50 years, but as far as I know no one has seriously asked the question: *Where does the HI come from?* This question is likely to seem naive whether you are a theorist or an observer, but probably for diametrically-opposed reasons! If you are an observer who studies HI in galaxies with the VLA, as most of us here today are, then you probably assume that the HI is in some sense *primordial*, i.e. it was present in the galaxy before any stars were formed, and the stars formed from it, and anyone who would question that point of view must be out of touch with the mainstream. On the other hand, if you are a theorist who studies the physical state of the ISM, you know that the time scales for the formation and destruction of H_2 in the ISM are so short that essentially all of the HI in a galaxy has been in the form of H_2 many times during a galaxy lifetime, and to ask where the HI comes from in a galaxy is a naive question similar to ''which comes first, the chicken or the egg?''

From the point of view of the basic physics, two HI atoms will have a lower energy state if they can get together and make an H_2 molecule. A physicist would therefore expect that, if there is a channel for this interaction to get rid of its binding energy and angular momentum, and if there is enough time, in the absence of a source of continual energy input the gas would all be in the form of H_2. In pure HI gas, there is a small but non-zero probability that a collision of two HI atoms will indeed form an H_2 molecule by emission of quadrupole radiation. This reaction is favored at low temperatures and high volume densities. The re-formation rate can be increased by many orders of magnitude if dust grains are present in the gas. H_2 molecules are destroyed by UV photons, creating two HI atoms by photodissociation. The equilibrium state of the gas then depends on the balance between dissociation and re-formation, and the relative amounts of $N(H_2)$ / N(HI) may vary considerably over a galaxy. Indeed, we may expect to find both H_2 and HI in various amounts near any and all sources of far-UV photons. What observational evidence is there for this association in galaxies?

Photodissociation regions (PDRs) have been identified in the Galactic ISM both in the general diffuse gas and in dense regions near hot young stars. Theoretical work on PDRs has been stimulated by recent satellite observations (e.g. COBE, ISO, and SWAS), and detailed models exist especially for the dense surfaces of molecular clouds (10^2 - 10^7 cm^{-3}) which are illuminated by intense far-UV fluxes (10^0 - 10^6 times the local average interstellar radiation field (ISRF) near the Sun). Hollenbach & Tielens (1999) have recently written an excellent review on this subject with many references. By now we can say that the basic physics is well understood, and calculations of infrared line ratios and even line intensities are quite successful at accounting for the observations under a wide range of physical conditions in the Galactic ISM.

Perhaps less well known is the fact that the same physics used to calculate the mid-IR lines of H_2 from the ISM also provides a straightforward way to calculate the amount of HI resulting from dissociation of the H_2 molecules under the action of the same UV photons which provide the mid-IR excitation. However, an important difference between the mid-IR and 21-cm radio observing techniques now comes into play; in the mid-IR, observational selection favors high-density, high-UV-flux situations which lead to high surface brightness. But measurements of the 21-cm HI line favor the lower-density, lower-UV-flux situations, since in these cases the HI is spatially more extended and the observational beam filling factors are therefore larger, making the emission easier to detect with radio telescopes.

2. THE ASSOCIATION OF HI WITH H_2

2.1. ... in the Galaxy

Envelopes of HI are often found around Galactic GMCs (1-10 pc scale; e.g. Andersson, Wannier, & Morris 1991; see Blitz 1993 for a summary) and have been ascribed to photodissociation of the GMC surface by the ISRF. Reach, Koo, & Heiles (1994) find evidence for H_2 in some interstellar cirrus clouds with high column densities ($N(HI) > 4 \times 10^{20}$ cm^{-2}) in quantities about equal to, or greater than the HI in spite of the fact that these clouds are likely to be fully exposed to the far-UV flux from the Galactic plane. In the very few instances where the viewing geometry is favorable, and when the line-of-sight superposition can be separated using radial velocity information, HI ''blankets'' can be seen between B Stars & GMCs (10-100 pc scale); a clear example of this is Maddalena's Cloud, which has been described as a large PDR of size ~ 50 × 200 pc dissociated by far-UV photons from one or two B5-O9 stars each located about 50 pc from the HI (Williams & Maddalena 1996).

2.2. ...and in other nearby galaxies

The first indication that photodissociation may be operating to affect the large-scale morphology (100-1000 pc) of the HI in galaxies was found in M83 by Allen, Atherton, & Tilanus (1986), who noticed a spatial separation between a particularly well-defined dust lane and the associated ridge of HI and HII in M83. Other studies have followed on M83 and on other galaxies (M51, M100; see Smith et al. (2000) for references) and have generally agreed that the initial interpretation in terms of photodissociation remains a viable option. The separation in the case of M83 is about 500 pc, and arises because of the difference between the spiral pattern speed and the rotation speed of the gas, coupled with the time for collapse of GMCs and the time that a massive young star lives on the main sequence.

The first study to successfully identify the characteristic PDR ''shell'' morphology of HI in close association with far-UV sources in a nearby galaxy was carried out on M81 by Allen et al. (1997). The problem is, of course, to obtain sufficient linear resolution (~ 100 pc) in the HI observations to permit one to identify the morphology of the PDR structures. An important point to note is that the best ''correlation'' is between the HI and the far-UV, not between the HI and the Hα.

A study similar to M81 but with more quantitative results has recently been carried out on M101 by Smith et al. (2000), who used VLA-HI and UIT far-UV data to identify and measure PDRs over the whole extent of the M101 disk. From these observations they derived the volume density of the H_2 in the adjacent GMCs in the context of the PDR model. Figure 1 shows the best estimate of the H_2 volume densities of GMCs near a sample of 35 young star clusters. The range in density (30 - 1000 cm^{-3}) is typical for GMCs in our Galaxy, lending support to the use of the PDR picture, and also shows little trend with galactocentric distance.

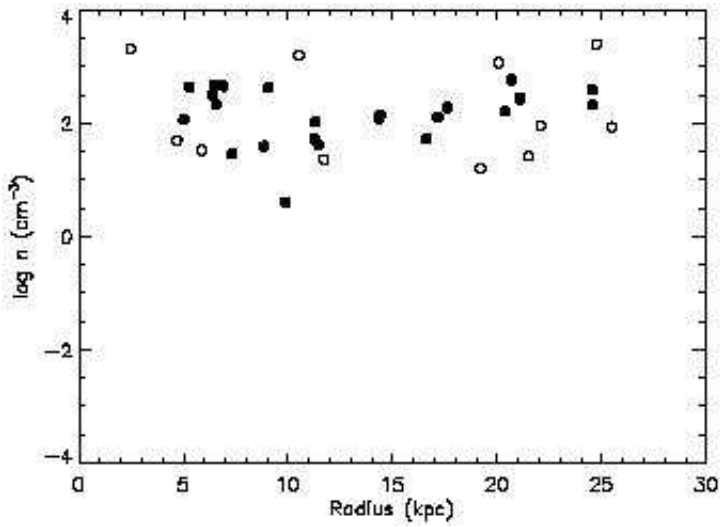

Figure 1. H_2 gas volume density in GMCs near a sample of 35 young star clusters in M101. See Figure 19 in Smith et al. (2000) for further details.

There is also IR spectral evidence that PDRs are important for understanding the physics of the ISM in galaxy disks. KAO observations of the 158 μm CII line suggest that as much as 70%-80% of the HI in NGC 6946 could be produced by photodissociation (Madden et al. 1993), and ISO spectra in the mid-IR indicate that the bulk of the mid-IR emission from galaxy disks arises in PDRs (Laurent et al. 1999; Roussel, Sauvage, & Vigroux 2000; Vigroux et al. 1999).

3. COLD MOLECULAR GAS IN THE INNER DISK OF M31

What evidence do we have that significant quantities of molecular gas could be ‘‘hiding’’ in the ISM of many galaxies? Well, we do know that many galaxies contain dark matter, and at present there seems to be nothing wrong with assuming that at least some part of that dark matter is in the form of a disk of molecular gas. Low-density molecular gas could escape detection since the excitation of the CO molecules may be subthermal, but in that case it is not likely that much mass is involved. If gravitationally-significant amounts of H_2 are present, say $M(H_2) \gtrsim M(HI)$, then the molecular gas would have to be more dense, and also generally cold in order to escape detection in the extensive CO(1-0) emission line surveys of galaxy disks. Such gas could exist in well-shielded parts of galaxies where the UV flux and cosmic ray density are both very low.

The inner disk of M31 is just such a ‘‘cold’’ environment, and it was here where an initial detection of faint CO emission emanating from large dark dust clouds was first reported (Allen & Lequeux 1993). Modelling of this data (Allen et al. 1995) confirmed that the ‘‘cold gas’’ interpretation was viable. Subsequent observations discovered similar emission in other dust clouds in the inner disk (Loinard, Allen, & Lequeux 1996), and also showed that such emission is ubiquitous in the inner disk of M31 (Loinard, Allen, & Lequeux 1995), covering more than half of the annular area between about 1 and 8 kpc in galactocentric radius. The distinction between cold, extensive gas and small, warm, beam-diluted condensations was made in favor of the former with a combination of JCMT CO(3-2) and OVRO CO(1-0) synthesis-imaging observations on the dust cloud D478 by Loinard & Allen (1998). The bulk of the molecular gas in this GMC-sized cloud appears as an absorbing screen at ~ 3.5 K. There is no reason to presume that D478 is peculiar, so we must conclude that cold molecular gas is indeed extensively present in the inner disk of M31.

How much mass could be in such a component? Loinard & Allen (1998) suggested that if the GMCs were at least marginally bound, then H_2 mass surface densities of order ~ 100 $M\odot$ pc^{-2} would be present in the inner disk of M31. However, very recently Pringle, Allen, & Lubow (2000) have argued that GMCs are unbound, transient objects that are not formed from *in situ* cooling of HI, but from the agglomeration of the dense phase of the ISM, much of which is already molecular. How much mass is in this component is presently the big question, but it's a delicate one that needs some careful thought, and I am not prepared to address it here any further just yet.

4. GAS, DUST, AND YOUNG STARS IN THE OUTER DISK OF M31

The presence of significant amounts of molecular gas in the INNER parts of a galaxy may not be so remarkable in the context of the conventional wisdom about the state of the ISM in galaxies; however, I think most of the HI observers would expect that the HI present in the far OUTER parts of a galaxy is much more ''primordial'', and that star formation away out there is going to be rare. Recent results by Cuillandre et al. (2000) contradict both of these bits of conventional wisdom. These authors used a large-format CCD on the CFHT to observe stars and background galaxies in a field covering the outer parts of M31 from 23 to 33 kpc, beyond R_{25}, a field in which the HI was mapped more than 25 years ago (Emerson 1974; Newton & Emerson 1977) with one of the pioneering HI imaging synthesis radio telescopes, the ''1/2-mile telescope'' at Cambridge, England. In particular, Cuillandre et al. compared V-I color-magnitude diagrams for HI-rich regions with the diagrams for HI-poor regions, and discovered evidence for dust mixed in with the HI in amounts corresponding to 0.3 - 0.4 of the amounts in the Solar neighborhood. This gas is therefore not primordial, at least not in the usual sense of not having been processed in stars. Furthermore, they discovered young B stars correlated with the HI, confirming that massive star formation is going on at the present time. The close association between HI and the young stars in the outer disk of M31 is shown in Figure 2. The presence of current, ongoing star formation implies that H_2 must therefore also be present, mixed in with the HI, in order to form these massive stars.

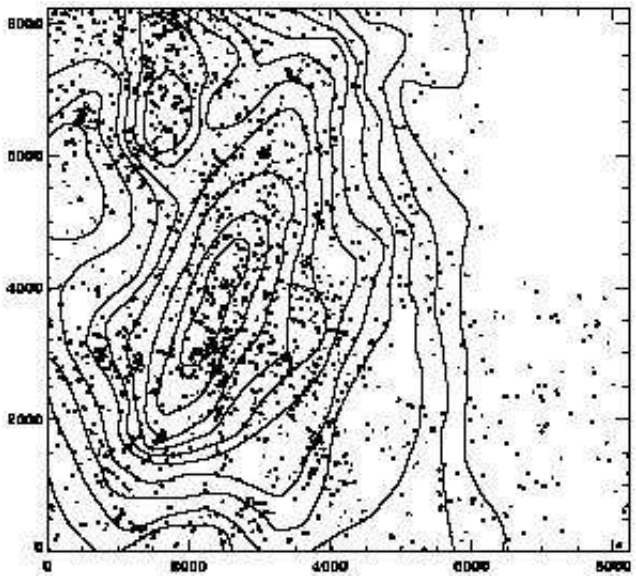

Figure 2. The distribution of blue stars over the extreme outer disk of M31 from Cuillandre et al. (2000). This is a 28' × 28' field, and covers a distance range from 23 to 33 kpc along the SW major axis of M31. The points represent the locations of stars in the range $20.5 < V < 24.5$ with $-0.5 < V - I < 0.2$; larger dots are brighter stars. The contours are HI column density from Newton & Emerson (1977), with a resolution of 3.6' *EW* × 5.8' *NS* FWHM, and have here been corrected for their primary beam attenuation. The HI contours are drawn at levels of 2 through 18 in steps of 2, plus contours at 13 and 19, in units of 7.7×10^{19} atoms cm^{-2}. There is some contamination by quasars and Galactic white dwarfs, which are visible e.g. in the halo field at the extreme south-west of the image. A small area in the NW corner of this image shows no stars because this part of the CCD mosaic was not used.

Could the photodissociation picture developed by Smith et al. (2000) for M101 also work in the outer disk of M31? A back-of-the-envelope calculation using the formalism in the Smith et al. paper is encouraging; compact clouds of H_2 with densities of order 100 cm^{-3} are needed, similar to M101. However, in M31 the field is clean and unconfused, and a complete census of *all* far-UV-producing stars can be done. Here we have perhaps the best laboratory yet for testing the photodissociation picture; a quantitative analysis is in progress.

5. FUTURE PERSPECTIVES

I have summarized some of the currently-available evidence in favor of viewing HI as a product of the star formation process rather than a precursor to it, and presented a case that H_2 is likely to be present in significant quantities in most galaxies. How much H_2 is really present in any given galaxy? I believe this is presently an open question, the answer to which is likely to have important consequences for several areas of astrophysics.

Acknowledgments. I am grateful to my colleagues at STScI for helping to provide a scientifically-stimulating atmosphere, and especially to our theorists Mike Fall and Nino Panagia for discussions on the ideas described in this paper.

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