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H_2 IN THE UNIVERSE: CONTRASTING THEORY AND OBSERVATIONS

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Abstract

Molecular hydrogen, H_2, is the most abundant molecule in the Universe, regulating various processes in diverse astrophysical environments. With the advent of the Infrared Space Observatory (ISO) and the Spitzer Space Telescope (SST) we have been able to detect extragalactic H_2 line emission opening up new avenues of exploring the physics of the interstellar medium (ISM) near and far. We review the role of such H_2 emission line detections in our understanding of the physical mechanisms responsible for its excitation and the differences among different galaxy types. We discuss possibilities of detecting H_2 from distant objects in the Universe thanks to the enhanced sensitivity of the SPICA/SAFARI instrument. Finally, we evaluate the role of H_2 in the cosmological context as we contrast theory and observations.

Key words: Galaxies: formation – Galaxies: starbursts – Missions: SPICA

1. Introduction

As the most abundant molecule in the Universe, molecular hydrogen H_2 can be found in diverse environments. Several mechanisms can be responsible for its excitation and by studying H_2 we can probe a variety of different astrophysical surroundings. H_2 forms on the surface of dust grains therefore affecting the chemistry of the interstellar gas, but also acts as a major coolant of the interstellar medium and this is especially relevant to studies of the Early Universe. It plays a major role in processes that regulate star formation and subsequent galaxy evolution.

The hydrogen molecule itself is symmetric, consisting of two identical atoms. As such, the molecule lacks a dipole moment and all ro-vibrational transitions within the electronic ground states are quadrupolar with low spontaneous coefficient A values. Direct H_2 detection is difficult. Electronic transitions occur in the UV where the earth's atmosphere is opaque and access from space is required. The ro-vibrational transitions arise in the near-infrared and are thus accessible from the ground however, these transitions typically trace H_2 gas of masses around 10^5 $M_\odot$ and temperatures $\sim$2000 K. However, gas at these temperatures is a very small fraction of the total amount of H_2 gas (e.g. Usuda et al., 1996; van der Werf et al., 1993). Rotational transitions on the other hand, arise in the mid-infrared and trace moderately warm (T$\sim$ a few hundreds K) gas. The H_2 molecule exists in two, almost independent states, namely ortho-H_2 (spins of H nuclei parallel) and para-H_2 (spins anti-parallel). There are no radiative transitions between ortho- and para- H_2 but ortho-para conversion may occur through proton exchange reactions between H_2.

With the advent of the Infrared Space Observatory (ISO) direct detection of the mid-infrared pure rotational H_2 lines was possible for the first time for extragalactic sources. The first systematic study of small sample of starbursts and AGN (Rigopoulou et al., 2002) demonstrated the efficacy of using the H_2 rotational transitions in probing directly warm molecular gas in external galaxies. The Spitzer Space Telescope (SST) confirmed these earlier findings and, thanks to its improved sensitivity, statistically complete samples with multiple detections of the H_2 rotational transitions for (Ultra)-luminous infrared galaxies (e.g. Higdon et al., 2006), nearby galaxies (e.g. Roussel et al., 2007; Appleton et al., 2006), distant radio galaxies (Egami et al., 2006; Ogle et al., 2007) became available.

We review the recent findings and discuss the impact that SPICA and in particular SAFARI H_2 surveys will have on our current knowledge of the formation and role of H_2 in extragalactic systems. We discuss these observations in the light of theoretical predictions for H_2 particularly at high redshifts.

2. Setting the scene: ISO and Spitzer findings

The first detection of extragalactic H_2 in NGC 6946 (Valentjin et al., 1996) demonstrated that it is possible to probe warm molecular hydrogen directly via its rotational lines. Rigopoulou et al. (2002) presented the first large systematic study of the properties of molecular gas in Starbursts and AGN and found that the warm gas accounts for 5-35 % of the total gas reservoir as probed by CO studies. With the advent of Spitzer and its improved sensitivity H_2 line detections on larger samples of galaxies have been possible. H_2 has been detected in nearby galaxies (from the SINGS survey, Roussel et al., 2007), Luminous and Ultraluminous galaxies (e.g. Higdon et al., 2006; Armus et al., 2006) but also more distant objects, clusters of galax-

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ies (e.g. Egami et al., 2006), radio galaxies (e.g. Ogle et al., 2007). Through excitation diagrams we have been able to derive various physical parameters such as the temperature of the molecular gas as well as its column density and mass, the latter by comparing it to the total molecular mass available through CO measurements.

Rigopoulou et al. (2002) examined the correlation between H_2 emission (they used the strongest $H_2S(1)$ line) and the strength of the 7.7 μm Poly-Aromatic Hydrocarbon (PAH) emission feature and concluded that a correlation exists between the two which holds (with some minor differences) for both Starburst and AGN. Figure 1 shows the PAH vs molecular hydrogen correlation from Rigopoulou et al. (2002) supplemented with data for nearby normal galaxies from Roussel et al. (2007). They find that starbursts and Seyferts with a strong starburst-component follow a very similar correlation. On the other hand the ratio H_2/PAH is higher in pure "AGN dominated" objects. It is likely that an extended circumnuclear component of "warm" gas (heated by the nuclear X-ray emission) is present in AGN in which enhanced H_2 emission originates. This "warm" gas component is either too far away for UV photons to reach or, acts as a shield to UV photons resulting in both cases in suppressed PAH emission. If that correlation holds at higher redshifts (some indication that this is the case was presented by Dasyra et al., 2009) then, there should be a whole lot of H_2 at higher redshifts as also predicted by semi-analytical simulations (e.g. Obreschkow & Rawlings, 2009).

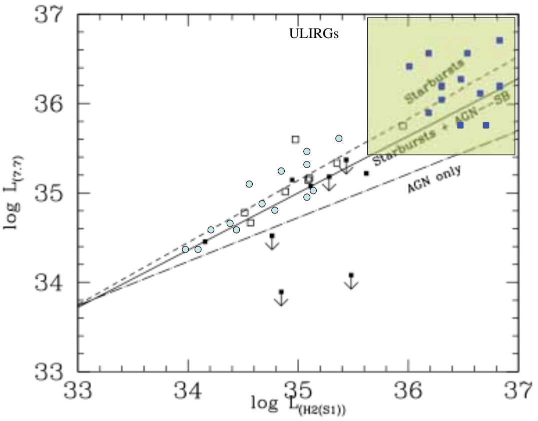

Figure 1. PAH luminosity $L_{7.7}$ vs. the $H_2S(1)$ luminosity for a sample of starbursts and AGN (Rigopoulou et al., 2002), ULIRGs (Higdon et al., 2006), normal galaxies (Roussel et al., 2007). The open and filled squares represent the Starburst and AGN points, respectively, the blue points are the ULIRGs. The lines shown represent the least square fits for: dashed line: starbursts, straight line: starbursts and AGN detections, long-dashed line AGN only (non-detection included).

2.1. H_2 BRIGHT SOURCES

A new class of extremely luminous H_2 emission galaxies has recently emerged. These galaxies display luminosities reaching up to $10^{10}L_\odot$ in pure molecular hydrogen emission lines and relatively weak total IR emission (e.g. Egami et al., 2009, in prep). The most extreme examples show bright H_2 emission lines without any spectroscopic signatures of lines originating in star forming processes (e.g. Appleton et al., 2006) or ionized gas. In some cases molecular gas has been detected through mid-infrared H_2 rotational lines prior to CO observations. Figure 2 shows a comparison of the spectrum of an H_2 luminous object (3C326, from Ogle et al., 2007) and for comparison the spectrum of normal star forming galaxies (from Brandl et al., 2006).

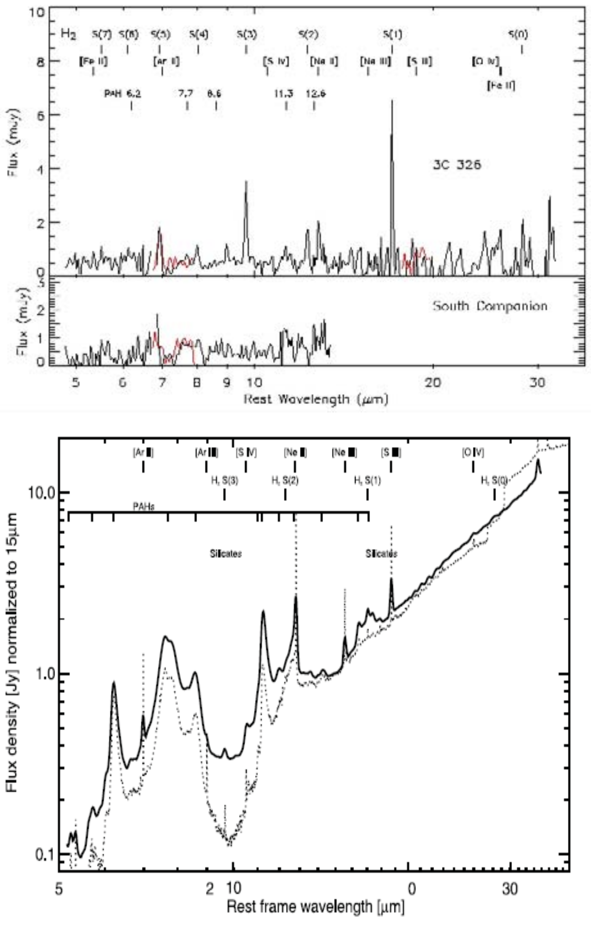

Figure 2. The top panel is the spectrum of 3C326 H_2 luminous radio galaxy from Ogle et al. (2007), whilst the lower panel shows for comparison the spectrum of star-forming galaxies (Brandl et al., 2006). The PAH bands at 6.2, 7.7, 11 μm are prominent in the spectrum of star-forming galaxies, but weak or absent in the (top) H_2 luminous radio galaxy.

Although the mechanism of H_2 excitation in these H_2-luminous galaxies is yet unclear, shock excitation is very likely to be responsible. However, the absence of spectroscopic signatures of photoionization that imply no or little star formation contradicts the general picture of shock induced emission. The fact that these objects show no star formation at the centres implies that the shock is not long-lived enough to allow formation of gravitationally unstable molecular fragments. These luminous H_2 objects may play a significant role in the evolution of mergers as their number density may in fact increase with cosmic time.

3. H_2 IN THE UNIVERSE

Obreschkow & Rawlings (2009) discussed a model for the distribution of H_2 (and HI) in regular galaxies based on the assumption that all cold gas resides in a flat symmetric disk with an exponential surface density profile and that the local H_2/HI ratio is dictated by the kinematic gas pressure (Blitz & Rosolowsky, 2006; Leroy et al., 2008). Obreschkow& Rawlings (2009) presented the predicted evolution for the H_2 mass-function using the galaxy catalogue based on the Millenium simulation (Springel et al., 2005). Figure 3 shows the predicted evolution of the H_2 mass function (i.e. the comoving space density of sources per logarithmic mass interval).

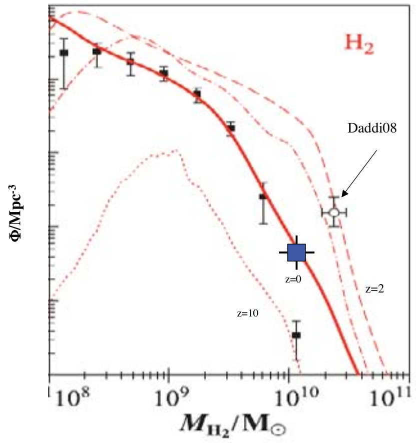

Figure 3. The comoving space density per logarithmic mass interval for H_2. The lines denote the results based on the Millenium Simulation (see Obreschkow & Rawlings, 2009): z=0 (solid), z=2 (dashed), z=5 (dash-dotted), z=10 (dotted). Black squares represent local values based on CO observations. The blue square represent measurements based on H_2 observations in ULIRGs (Rigopoulou et al., 2009). The open circle represents the density estimated at z=1.5 based on Daddi et al. (2008).

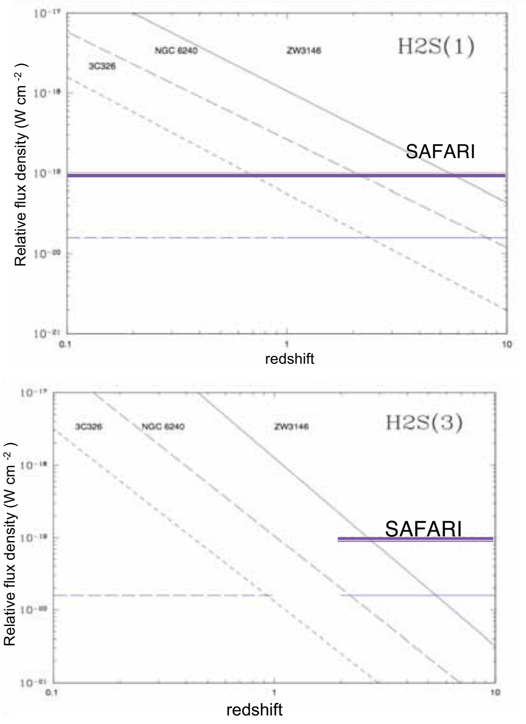

Figure 4. Estimated line strengths for the $H_2S(1)$ (top) and the $H_2S(3)$ (bottom) for a SAFARI survey. Three local templates are being used: 3C326, NGC 6240 and ZW3146. The purple line represents current SAFARI sensitivities.

The simulation agrees well with predictions of the comoving space density of H_2 as derived from local CO observations. Using H_2 measurements for ULIRGs (reported in Higdon et al. 2006) we derive an estimate of $M_{H_2} \sim 1.23\times10^{10}$ $M_\odot$ (by scaling the M_2 derived from rotational lines to the total $M(H_2)$ estimate from CO observations, for a detailed analysis, see Rigopoulou et al., 2009) which agrees nicely with the predicted H_2 mass function at z$\sim$0. H_2 surveys with SAFARI are thus invaluable in tracing H_2 in particular at high redshifts where the molecular gas reservoir is large as indicated by current observations of molecular gas of high redshift galaxies but also predictions based on semi-analytical simulations.

4. DETECTING H_2 WITH SAFARI

Theoretical work (Mizusawa et al., 2005) predicts that the ground state transition lines $H_2S(1)$, $H_2S(2)$ and $H_2S(3)$ should have a luminosity $>10^{3}5$ erg s^{-1} and thus should be within the reach of a deep "blind" SAFARI survey. Based on detections of H_2 in nearby galaxies, we find that the power emitted in the two lower state H_2 lines, S(0) and S(1) is typically around 20–25% of that found in the MIR cooling line such as [SiII] or [SIII]. For the disk galaxies in Roussel et al.(2007) this corresponds to about $3 - 3.5 \times 10^{-4}$ of the total infrared power, a limit that should be easily attainable in deep SAFARI surveys. Additional observational evidence for the existence of large molecular H_2 reservoirs in high-redshift galaxies is provided by the tight correlation found to exist between H_2 and PAH emission in local star-forming and disk galaxies (Rigopoulou et al., 2002; Roussel et al., 2007; Dasyra et al., 2009). PAHs are ubiquitous in high-z galaxies (e.g. Pope et al., 2008; Huang et al., 2009), and so if the PAH-H_2 correlation remains at the higher redshifts then the L_{H2}/L_{FIR} calculated above should serve as a lower limit.

Using the latest sensitivity numbers for the performance of SAFARI we make estimates of the detectability of $\mathrm{H_2}$ in a variety of environments assuming various local templates. In Figure 4 we show the expected strength of the $\mathrm{H_2S(1)}$ ($\lambda_{rest} = 17.03$ μm) and $\mathrm{H_2S(3)}$ ($\lambda_{rest} = 9.67$ μm) for a variety of local templates. In particular we consider 3C326 ($\mathrm{H_2}$ values from Ogle et al., 2007), NGC 6240 ($\mathrm{H_2}$ values from Armus et al. 2006) and ZW3146 ($\mathrm{H_2}$ values from Egami et al. (2006). $\mathrm{H_2S(1)}$ is easily detectable in the "best-case" scenario (ZW3146) out to redshift z$\sim$3 while for the remaining sources we can still detect $\mathrm{H_2S(1)}$ out to redshift $z \sim 1.5$.

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