The Spectral Energy Distribution of Galaxies
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The energetics of turbulent molecular gas and star formation

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Abstract. The role interstellar turbulence plays in regulating star formation is a much debated research topic. In this paper, I take an observational view point in presenting observations of H_2 line emission from extragalactic sources. I highlight key results from these observations. (1) H_2 line emission is a main cooling channel of molecular gas. It is a tracer of mechanical energy dissipation complementing mass tracers in describing the dynamical state of molecular gas in galaxies. (2) Spectroscopy of warm H_2 observations with the Spitzer Space Telescope and the SINFONI spectro-imager at ESO provide evidence of shock excited H_2 line emission in galaxies that exemplify the main agents of galaxy evolution. (3) The dissipation of mechanical energy involves a turbulent energy cascade and the cycling of interstellar matter across ISM phases, including the formation of H_2 gas from warm atomic gas. (4) In Stephan's Quintet and the radio galaxy 3C326, two sources with a high H_2 luminosity to mass ratio (i.e. a high dissipation rate per unit mass), turbulence is observed to quench star formation. In the Antennae merger, star formation is observed to proceed where the turbulent kinetic energy is being dissipated.

Keywords. turbulence, ISM: molecules, ISM: evolution, ISM: structure, stars: formation, galaxies: evolution, infrared: galaxies

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1. Introduction

What regulates the star formation rate in galaxies? This is a long standing question within the field of galaxy evolution. The low efficiency of star formation ($\sim 1\%$ per free-fall time, Krumholz *et al.* 2012) is most often associated with interstellar turbulence. Turbulence has a dual effect on star formation. On the one hand, it opposes gravity by continuously shearing apart gas, and on the other hand, where the gas kinetic energy is dissipated (e.g. in shocks), it creates structures that can become gravitationally bound and form stars (Mac Low & Klessen 2004). This paradigm establishes a direct connection between star formation and the energetics of molecular clouds, i.e. the energy injection that feeds turbulence and dissipation. To get a full picture of star formation we must combine observations which trace both the gas and the dissipation rate of its turbulent kinetic energy.

To characterize molecular gas, we primarily rely on rotational line emission of trace molecular species. The rotational lines of CO, are used to trace the spatial distribution and the kinematics of the bulk of the molecular gas. Lines from molecules with higher dipole moment, such as HCN, serve to trace the dense H_2 gas that is directly associated with star formation. It is far less straightforward to quantify the energy radiated away by molecular gas, and, thereby, the energetics of molecular clouds. Spitzer observations of H_2 rotational lines have contributed to open this missing perspective on molecular gas in galaxies.

H_2 emission from the interstellar medium is most often thought to be associated with localized heating of H_2 in photo-dissociation regions and shocks within star forming regions, but observations from the Infrared Space Observatory and more recently the Spitzer Space Telescope provide evidence for diffuse H_2 emission tracing the dissipation of turbulence kinetic energy. Bright H_2 line emission powered by interstellar turbulence, rather than by star formation, has been identified in the Milky Way diffuse interstellar medium (Falgarone *et al.* 2005, Ingalls *et al.* 2011), as well as in a number of extragalactic systems (Egami *et al.* 2006, Appleton *et al.* 2006, Ogle *et al.* 2010, Zakamska 2010, Herrera *et al.* 2011). These observations are the main focus of the paper.

2. H_2 Luminous Gas in Galaxies

Spitzer observations have provided fluxes of H_2 rotational lines for a number of extragalactic sources including sources with bright H_2 line emission with no, or relatively weak, spectroscopic signatures (dust and ionized gas lines) of star formation. Molecular gas is found to act as a cooling agent in a diverse set of objects which exemplify violent phases in the evolution of galaxies. In Fig.1, the H_2 emission in the four first rotational lines S(0) to S(3) is compared to the flux in the 7.7 μm PAH band. This ratio indicates what is powering the H_2 line emission. A tight correlation between the H_2 and PAH fluxes is observed in star forming galaxies, e.g. the SINGS sample (Roussel *et al.* 2007). These galaxies are distributed along the bottom horizontal dashed line in the plot. A number of galaxies lie significantly above this line. For these galaxies, the *excess* H_2 emission cannot be powered by UV heating of molecular gas. Sources with *excess* H_2 emission include galaxies with active galactic nuclei, cooling flows, star-burst winds, interacting galaxies and mergers. A common characteristic of these sources is that energy is injected in the interstellar medium (ISM) on galaxy-wide scales by a violent process.

In several of the H_2 galaxies the star formation rate per unit surface is much below the standard Schmidt-Kennicutt relation. For example, in the radio galaxy 3C326 (measured gas surface density $250\,M_\odot\,\mathrm{pc}^{-2}$), the Schmidt-Kennicutt law implies a star formation rate of $4.5\,M_\odot\,\mathrm{yr}^{-1}$, a value ~ 60 times greater than the observed upper limit from Spitzer 70μm imaging (Nesvadba *et al.* 2010, Nesvadba *et al.* 2011). A similar difference is observed for the molecular gas in the Stephan's Quintet (SQ) shock (Guillard *et al.* 2012). The fact that there is little star formation in these sources suggests that the H_2 gas is too turbulent to permit the formation of gravitationally unstable condensations. In other words it is sheared apart and shredded by turbulence on timescales shorter than the local free-fall time.

3. Turbulent energy cascade and H_2 cooling

A range of H_2 temperatures is required to account for the H_2 excitation diagram. The bulk of the warm H_2 gas mass is at the lowest temperature ~ 150 K. The mass of warm H_2 is estimated to be 5×10^8, 10^9, 2×10^9, and $10^{10}\,M_\odot$ in SQ, the radio galaxy 3C326, the merger NGC 6240 and the brightest cluster galaxy ZW3146, respectively. For these four galaxies that are archetype sources, the warm H_2 gas is observed to account for a significant fraction ($> 10\%$) of the cold H_2 mass inferred from the CO luminosity. This is a significant result because the cooling time of H_2 gas at a temperature of 150 K is $\sim 10^4$ yr, a value much smaller than the dynamical timescales associated with energy injection. To account for the high fraction of warm H_2, the gas must be repeatedly heated. This implies that the dissipation of mechanical energy does not occur in shocks directly driven by bulk motions, but involves an energy cascade which feeds turbulence within molecular clouds. The galaxy-wide shock in the SQ compact group is a template source which highlights this key idea.

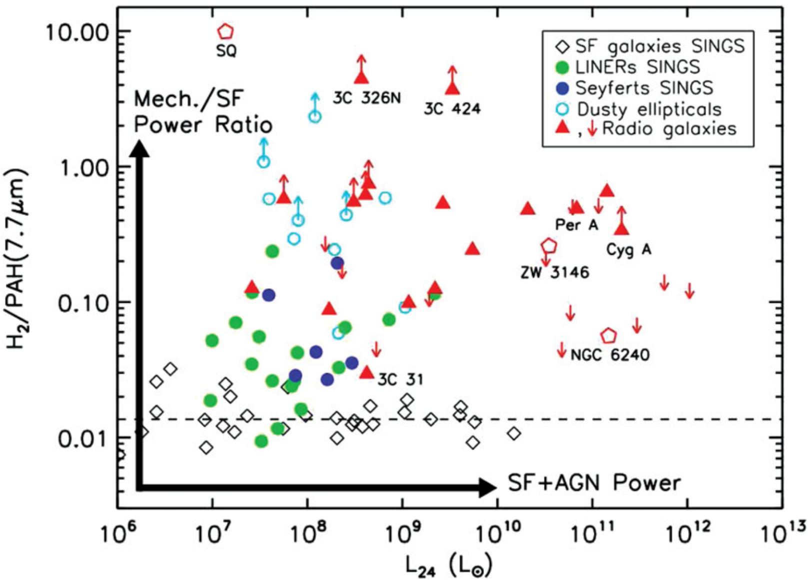

Figure 1. The ratio between the H_2 fluxes summed over the 0-0 S(0)-S(3) lines to the 7.7 μm PAH flux is plotted versus the 24 μ rest frame luminosity. The gas to dust, H_2 to PAH, emission ratio indicates the relative importance of mechanical heating and UV (star formation) as energy sources powering the H_2 emission. This figure is borrowed from Ogle *et al.* (2010).

In SQ, the kinetic energy from a high speed ($\sim$ 1000 km s^{-1}) collision, between an intruding galaxy and a tidal arm within the galaxy group, is observed to be powering X-ray emission with an emission temperature of 5×10^6 K corresponding to a shock velocity of $\sim$ 600 km s^{-1}. This shock velocity is consistent with the gas velocity in the center of mass frame; it is about half of the observed relative velocity, as expected if the gas mass on the intruder and SQ tail sides are similar. The H_2 line emission has the same spatial extent as the plasma, and is a few times more luminous than the X-ray luminosity (Appleton *et al.* 2006, Cluver *et al.* 2010). CO observations show that the turbulent energy of the post-shock molecular gas is larger than the thermal energy of the shock-heated X-ray emitting plasma (Guillard *et al.* 2012). Most of the kinetic energy of the collision has not been thermalized. It is observed to be in bulk and turbulent motions of the molecular gas. It is the progressive dissipation of this energy that powers the H_2 emission.

The presence of large amounts of warm H_2 gas in the post-shock gas implies an energy cascade transferring a significant fraction of the kinetic energy of the collision to turbulent motions of much smaller amplitude within molecular clouds. The amplitude of turbulence may be estimated from the luminosity to mass ratio of the H_2 gas which is observed to be $4\times10^{-2}\, L_\odot/M_\odot$ (Guillard *et al.* 2012). The H_2 luminosity is summed over the S(0) to S(5) rotational lines and the H_2 mass inferred from the CO(1-0) luminosity assuming that the Milky Way conversion factor applies to SQ. The L_{H_2}/M_{H_2} ratio may be used to estimate the amplitude of turbulent motions within SQ molecular clouds. We consider that the H_2 luminosity is powered by the dissipation of the gas turbulent kinetic energy over a timescale $t_{diss} = R/\sigma_v$, where R is the cloud radius and σ_v the 1D velocity dispersion. Since the dissipation of the gas kinetic energy does not occur only through the S(0) to S(5) lines used to estimate the H_2 luminosity, we introduce the factor $f_{H_2} = L_{H_2}/L_{diss}$ where L_{diss} is the bolometric luminosity.

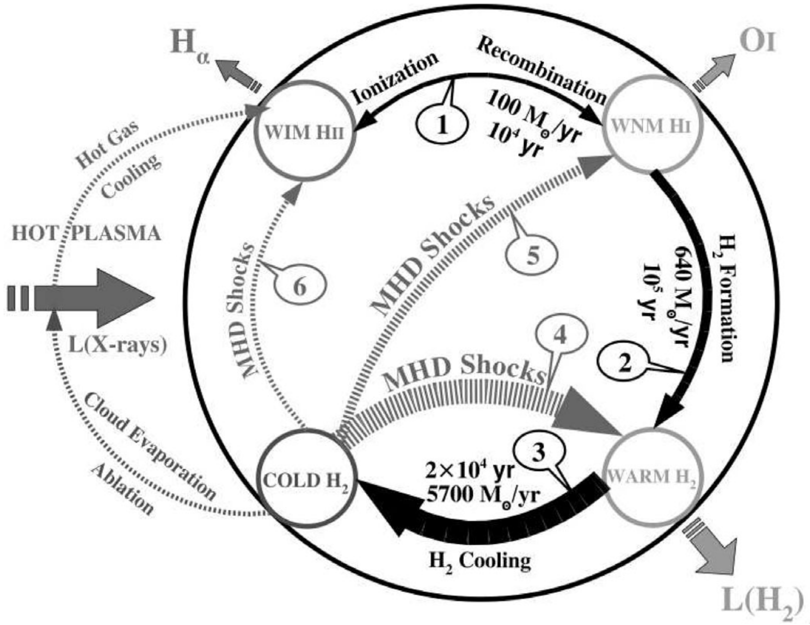

Figure 2. Schematic view at the gas evolutionary cycle proposed in our interpretation of Stephan's Quintet optical and H_2 observations. Arrows represent the mass flows between the HII, warm HI, warm and cold H_2 gas components. They are numbered for clarity. The dynamical interaction between gas phases drives the cycle. The mass flow values and associated timescales are derived from the H_α, [OI], and H_2 luminosities and model calculations. Heating of the cold H_2 gas (dark grey arrows) is necessary to account for the increasing mass flow from the ionized gas to cold H_2 phases. This figure is borrowed from Guillard *et al.* (2009).

$$
\begin{aligned}
L_{H_2}/M_{H_2} &= f_{H_2}\, L_{diss}/M_{H_2} = 3/2\, f_{H_2}\, \sigma_v^3/R \\
&= 4\times10^{-2}\, f_{H_2}\, (\sigma_v/20\,\mathrm{km\,s^{-1}})^3\, (R/50\,\mathrm{pc})^{-1}
\end{aligned}
\tag{3.1}
$$

Since $f_{H_2} < 1$, a turbulence amplitude $> 20\,\mathrm{km\,s^{-1}}$, for a cloud radius $R = 50\,\mathrm{pc}$, is required to account for the H_2 emission. The lower limit on σ_v is a factor 6 larger than that measured for giant molecular clouds in the Milky Way (Heyer *et al.* 2009). The modeling of the H_2 excitation diagram with MHD shocks yields comparable velocities (Guillard *et al.* 2009).

4. The dynamical interaction between gas phases

For a few of the H_2 sources we have imaging data displaying the spatial distribution of the H_2 emitting gas. In the Perseus cluster and the M82 galactic wind, the data show that the warm H_2 extends to the halo where it is mixed with hot and warm gas traced by X-ray and optical and infrared emission lines. This is also true for SQ where the H_2 and X-ray emission have similar spatial extent (Cluver *et al.* 2010). These imaging data show a close association between the cold and hot ISM. Based on multi-wavelength observations of SQ, Guillard *et al.* (2009) showed that the energy dissipation must involve gas cycling across ISM phases, including formation of H_2 out of warm atomic gas.

A schematic cartoon of the dynamical evolution of the post-shock gas in SQ is presented in Fig. 2. Black and dark grey arrows represent the mass flows between the HII, warm HI, warm and cold H_2 gas components of the post-shock gas. The large inward-pointing grey arrow to the left symbolizes the relative motion between the warm and cold gas and the surrounding plasma. Each of the black arrows is labelled with its main associated process: gas recombination and ionization (arrow number 1), H_2 formation (2) and H_2 cooling (3). The values of the mass flows and the associated timescales are derived from observations and model calculations.

A single cycle through gas components is excluded by the increasing mass flow needed to account for the H_α, OI, and H_2 luminosities. Heating of the cold H_2 gas towards warmer gas states (dark grey arrows) needs to occur. It is the dissipation of the gas mechanical energy that powers these dark grey arrows. The post-shock molecular cloud fragments are likely to experience a distribution of shock velocities, depending on their size and density. Arrow number 4 represents the low velocity MHD-shocks excitation of H_2 gas. More energetic shocks may dissociate the molecular gas (arrows number 5). They are necessary to account for the low H_α to O I luminosity ratio. Even more energetic shocks may ionize the molecular gas (arrow number 6). This would bring cold H_2 directly into the H II reservoir. Within this dynamical picture of the post-shock gas, molecular gas is not necessarily a mass sink. The mass accumulated in H_2 gas depends on the ratio between the excitation by shocks trough one of the dark grey arrows 4, 5 and 6 and the H_2 formation and cooling timescales along the black arrows 2 and 3.

An efficient transfer of the bulk kinetic energy to turbulence in molecular clouds is required to make H_2 a dominant coolant of the post-shock gas. Dissipation within either the hot plasma or warm atomic gas, leading to radiation at X-rays or optical wavelengths that is not efficiently absorbed by the molecular gas, has to be minor.

We are far from being able to describe how the energy transfer occurs. We just make qualitative statements that would need to be quantified with numerical simulations in future studies. The fragmented, multiphase structure of the clouds is likely to be a main key of the energy transfer. The dynamical interaction with the background plasma flow generates relative velocities between cloud fragments, because their acceleration depends on their mass and density. The relative motions between cloud fragments can lead to collisions, which will result in the dissipation of the kinetic energy. This dissipation will occur preferentially in the molecular gas, because it is the coldest component with the lowest sound speed. The magnetic field is likely to be important, because it weaves the cloud H_2 fragments to the lower density cloud gas which is more easily entrained by the background plasma flow. The mass cycle between cloud gas states contributes to the energy transfer. The gas that cools carries its turbulent kinetic energy to the colder gas phase it cools to. In other words, gas cooling transfers the turbulent velocities of the warm H II and H I to the colder and denser H_2 gas that is formed.

5. From the dissipation of gas kinetic energy to star formation

Herrera *et al.* (2011 & 2012) have presented CO and H_2 observations of the overlap region in the Antennae, obtained with the near-infrared imaging spectrograph SINFONI on the ESO Very Large Telescope and ALMA during science verification. These observations give a foretaste of the power of combining mass and energy tracers to study the dynamical state of molecular gas in galaxy mergers and the early stages of star formation.

Most of the star formation in the overlap region occurs in massive super-star clusters (SSCs) with masses up to a few 10^6 $M_\odot$ (Whitmore *et al.* 2010). The large surface density of molecular gas and its fragmentation in super giant molecular complexes (SGMCs) with masses of several 10^8 $M_\odot$, two orders of magnitude larger than masses of giant molecular clouds in spiral galaxies, are evidence for cooling and gravitational fragmentation of the diffuse gas compressed in the galaxies collision (Teyssier *et al.* 2010). The data show that

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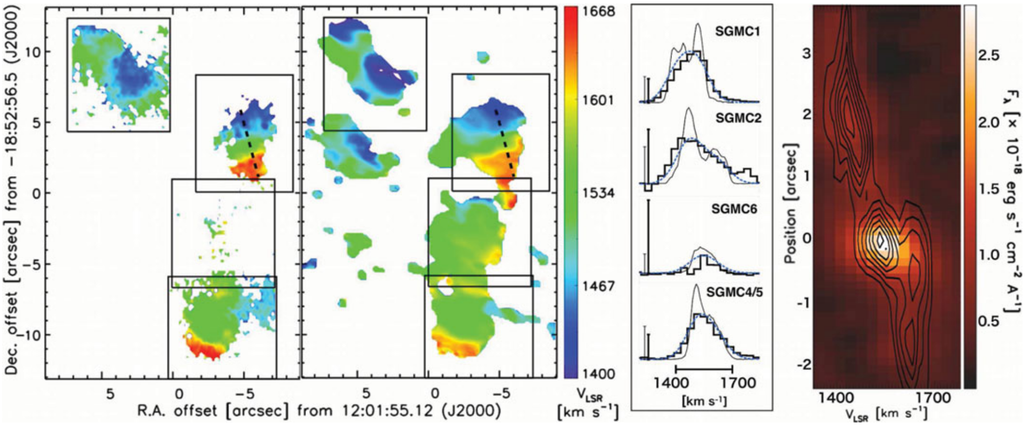

Figure 3. *Left panel:* Velocity maps derived from the H_2 (left) and CO (right) line emission. Dotted lines mark the position-velocity cut shown in the right panel. *Mid panel:* Integrated line profiles of CO (thin solid line) and H_2 (thick black solid line with steps) for each SGMC. Dashed spectra show the CO lines convolved to the spectral resolution of SINFONI. Black bars correspond to 5×10^{-16} erg s^{-1} cm^{-2} Å^{-1} for the 1-0 S(1) H_2 line, and grey bars to 1.5 Jy for CO, for all of the SGMCs. Offsets between the black and dashed spectra indicate variations in the CO-to-H_2 ratio between velocity components. *Right panel:* H_2 position-velocity diagram, across the bright compact H_2 source discussed in the text, with CO emission shown as contours in steps of 0.02 Jy beam^{-1} starting at 0.03 Jy beam^{-1}. This figure is borrowed from Herrera *et al.* (2012).

all SGMCs have H_2 1−0 S(1) line emission and the H_2 1−0 S(1) kinematics match those of CO(3−2) well (Fig. 3).

Herrera *et al.* (2011) present an interpretation of the H_2 emission, which relates the emission to the energy dissipation required to form the SGMCs and clouds within the SGMCs from gas driven by the galaxy interaction. This interpretation introduces a dynamical view of the present state of the complexes. They are physically associated with gas which is too turbulent to be bound. This unbound gas is dynamically fed by the gas dynamics on larger scales. This idea is supported by the gas kinematics. The CO data show that all complexes have two spatially separated velocity components. The velocity difference between components within an individual SGMC is up to 150 km s^{-1} (Fig. 3). Given the size and mass of the SGMCs, this is too large to be accounted for by the gas self-gravity. The gas kinematics is most likely driven by the galaxy interaction. In single-dish observations similar velocity gradients are found in the extended emission around the SGMCs, which further supports this idea.

Herrera *et al.* (2011 & 2012) also discuss the nature of the bright, compact source of near-IR H_2 line emission discovered with their SINFONI data. This source shows no Brγ emission. It has the highest H_2/CO line emission ratio, and coincides with the steepest CO velocity gradient of the entire overlap region. With a size of 50 pc and a virial mass of $5 \times 10^7\, M_\odot$, it is perhaps a pre-cluster cloud that has not yet formed significant numbers of massive stars. The bolometric luminosity of this source is $\sim 10^7\, L_\odot$. It may be accounted for by the dissipation of the cloud kinetic energy for a cloud mass of a few $10^7\, M_\odot$ – a value comparable to the virial mass – and a dissipation timescale of 1 Myr. This timescale is comparable to the cloud crossing time, and also the dynamical time scale associated with the velocity gradient of 1 km s^{-1} pc^{-1} at the position of the cloud. The similarity of both timescales indicates that the cloud may still be forming by accreting gas, and thus that a significant part of the cloud luminosity may be powered by

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gas accretion. The compact source could represent a short (~ 1 Myr) evolutionary stage in the early formation of super-star clusters.

6. Conclusion

Analysis of spectroscopic observations obtained with Spitzer and SINFONI show that H_2 emission is a tracer of mechanical energy dissipation that complements mass tracers in describing the dynamical state of molecular gas in galaxies. This paper focuses on two objects, the Stephan's Quintet and the Antennae merger, where interaction between galaxies is feeding interstellar turbulence on galactic scales. The data highlight the role the H_2 gas plays as a cooling agent, from the formation of H_2 gas within the multi-phase ISM to the formation of gravitationally bound systems where star formation occurs.

What is being learned from these archetype sources may be of general relevance to violent phases of galaxy evolution, when merging, gas accretion, AGNs or star bursts release large amounts of mechanical energy on galactic scales. Observations of these and other H_2 luminous sources with Herschel and ALMA will soon complement the results I have presented. Data to be obtained with Herschel – spectroscopy of far-IR cooling lines and dust imaging – will provide key information on the energy dissipation process and the physical state of the H_2 luminous gas. ALMA offers the required combination of spectral and angular resolution to relate the gas energetics to the mass distribution and gas dynamics. What we will learn from these observations is likely to be of general relevance to understanding the energetics of the turbulent molecular gas in galaxies and what regulates its efficiency of forming stars.

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