Mem. S.A.It. Suppl. Vol. 25, 59

Memorie della
Supplementi

Distant intense starbursts: evidence for self-regulated star formation?*

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Abstract. From an analysis of the Hα and [N II]λ6583 rest-frame optical emission lines in a large sample of intensely star forming galaxies at z=1.3 to 2.7 observed with SINFONI on the ESO-VLT, we have reached a number of conclusions. The galaxies all have broad optical emission lines (σ ~50-250 km s^{-1}) which are a function of the underlying star formation intensity as determined from the Hα surface brightness. These broad lines are intrinsic to the galaxies and not due to beam smearing. The velocity dispersions appear to be related to the star formation intensity (Σ_{SFR}, star formation rate per unit area) of the form, $\sigma \sim \epsilon \Sigma_{SFR}^{1/2}$. This is a simple and direct relationship between the energy injection rate and the kinetic energy of the emission line gas with a coupling efficiency of ϵ. In this contribution, we outline a simple model whereby the energy output of massive stars, both mechanical and radiative, feeds a mass and energy cycle within the interstellar media of these distant galaxies. The mass and energy cycle pushes the global ISM towards the line of stability, Toomre parameter Q~1, but only if the molecular gas captures, to some extent, the kinematics of the warm ionized gas as probed by the optical emission lines. In such a picture, the star formation intensity is self-regulating.

1. Introduction

We have only relatively recently been able to probe the spatially-resolved properties of distant galaxies. This capability has been brought about by more comprehensive surveys of (strongly) lensed galaxies and with integral field spectrometers (IFS) in the optical and near-infrared and by sensitive interferometers and spectrometers in the infrared, submillimeter, and millimeter. This contribution concerns to the results of near infrared integral field spectroscopy of a significant number of distant galaxies. At redshifts between 1 and 3, near infrared spectroscopy generally probes the warm ionized gas in galaxies. These results have been presented in a number of papers (Lehnert et al. 2009; Le Tiran et al. 2011a,b, and in Lehnert et al. 2013, A&A, in press; L13 hereafter).

Before discussing the results of our near infrared integral field spectroscopic survey, which generally focusses on relation between the dynamics and ionization of the warm ionized medium (WIM), it is worthwhile to discuss some controversies and wisdom from the literature to set the stage.

* This work and many of the ideas presented here were developed in collaboration with L. Le Tiran, W. van Driel, P. Di Matteo (GEPI), N. Nesvadba, and F. Boulanger (IAS, Orsay, France).

Here is some wisdom gained from the literature and our own observations.

- For near infrared IFS, due to the bright night sky and fine spatial sampling, require galaxies to have relatively high surface brightnesses in their optical emission line gas to yield spatially resolved data with reasonable significance in a few hours of integration time on an 8-m class telescope. How high? Using standard coversion factor between Hα surface brightness and star formation intensity, this generally requires star formation intensities, $\Sigma_{SFR} \gtrsim 0.1$ M$_{\odot}$ yr^{-1} kpc^{-2}. How intense is this? This is generally around the level of nearby starburst galaxies but must be over a much larger area for the galaxies at high redshift to be spatially resolved (Lehnert et al. 2009);
- Galaxies, like the ones we have observed, must generally have high gas fractions compared to the typical local galaxy (Daddi et al. 2010; Tacconi et al. 2010);
- Locally, the gas may dominate the mass surface densities;
- The optical emission lines are generally much broader than those observed in nearby normal galaxies. The line are as broad as sometimes observed in local starburst galaxies (Lehnert et al. 2009).
- The optical emission line gas traces the WIM ($n_e \sim 0.1$-100 cm^{-3} and $T_e \sim 3000$-15000 K). The WIM is a minor constituent and likely traces the energy injection scale and rate and not the cooling or dissipation of energy (L12). The turbulent dissipation rate dominated by the warm and cold neutral medium and the cold molecular medium.
- The global star formation rate is controlled by the balance between gravity and turbulence (Mac Low & Klessen 2004). What processes regulate it are determined by the rate at which energy cascades, is dissipated, and over what time and size scales (e.g., Elmegreen & Scalo 2004). The ISM is a dynamic equilibrium and should in no way be viewed as static.

Within these general ideas and wisdom, there are also some controversies. In the observations, for example, what is the sources of the broad lines? Is it a real effect, or simply due to beam smearing? On the theoretical side, it is large scale instabilities and gravitational shear that regulates star formation or the radiative/mechanical output from the evolving stellar population? What is the role of cosmological accretion of gas in generating the broad lines we observe? Related to these are a number of key questions: How efficiently is mechanical energy output from the stars thermalized? What is the role of radiation pressure? Is it effective in accelerating the dusty massive clouds? How is the energy from massive stars, gravitational instability, and gas accretion shared? Is it mostly in bulk motions, turbulence, high outflowing gas with high thermal pressures? How is the energy transfered or shared between the phases of the dynamic ISM? Is the turbulent dissipation timescale longer or shorter than in local galaxies?

This last question is perhaps crucial. In a simple thought experiment, suppose that under a variety of energy injection rates, the dissipation time scale of turbulence is tuned by a small scale processes which maintains it at a constant value. In nearby galaxies, the thickness of the gaseous disk is of-order 10s to 100 pc and the dispersion velocities are of-order 10 km s^{-1}. If we equate the dissipation time scale and the turn-over time of the disk, then this would suggest that at high redshift, where the dispersion is of-order 100 km s^{-1} then the thickness of the gaseous disk should be about 1 kpc. Disks this thick have been observed at high redshift in the gas and continuum (Elmegreen & Elmegreen 2006; Elmegreen et al. 2009; Epinat et al. 2012). However, you would need a process to sustain such high velocities as the energy requirement to fuel such kinetic energies (especially given the relatively high gas content of distant galaxies) is much higher than nearby normal galaxies. However, the star formation intensities of high redshift galaxies, as observed with IFS, are high compared to local galaxies.

2. Observations and results

We observed a sample 53 intensely star forming galaxies with near-infrared integral-field spectrometer, SINFONI, on the ESO-VLT. The galaxies span a redshift range of z=1.3-2.7 and are typical of galaxies on the main sequence of star formation (Elbaz et al. 2007). All galaxies were observed for a few hours and the observations reach surface brightness detection limits in Hα of $\sim 2\times10^{-19}$ erg s^{-1} cm^{-2} pixel^{-1} The spectral resolution is FWHM~115 and ~150 km s^{-1} in the K and H bands, respectively. The observed surface brightnesses range from about 3.6-34 $\times$ 10^{-18} erg cm^{-2} s^{-1} arcsec^{-2} and the objects have isophotal radii, at their surface brightness detection limits, of 1-2 arcsec^2, or on average ~7±2 kpc (corresponding to an isophotal area of ~150±40 kpc^2). The point-spread function FWHM of the data is $\sim 0.''6$, which at z=2 represents an area of ~20 kpc^2, so we have generally ~8 spatial resolution elements per object.

From an analysis of the optical emission lines in these galaxies and in comparison with a beam smeared gas-rich disk galaxy simulation, we find:

- The Hα emission lines are broad ranging from our resolution limit of about 40 to 200 km s^{-1} and are a function of the Hα surface brightness and the star formation intensity. We compared our data with a simulation with a) the intrinsic velocity dispersion of the gas in the simulation (~10 km s^{-1} which is roughly constant with radius) and b) a velocity dispersion proportional to the star-formation intensity, $\epsilon\Sigma_{SFR}^{1/2}$, where ϵ is a coupling efficiency (taken to be 140 km s^{-1} (M$_\odot$ yr^{-1})$^{-1/2}$). The data are consistent with a model of the velocity dispersion given by the proportionality with the star formation intensity suggesting a relation between the star formation intensity and the internal dynamics of the gas.
- Galaxies at the lower end of our redshift range, z~1.4, have lower values of star formation intensity and dispersion, consistent with this picture but also reach values where the dispersions may become dominated by purely gravitational processes as evidenced by having some of the data points in the dispersion star formation intensity plane have dispersions plausibly similar to the dispersions intrinsic to our simulations. The lower redshift galaxies also have generally lower Hα surface brightnesses and thus star formation intensities.
- From an analysis of the ratios of [NII]/Hα and the [SII] doublet (Lehnert et al. 2009), we find the thermal pressure in the WIM is P/k~10$^{6-7}$ K cm^{-3} which is much higher than normal nearby galaxies but similar to star burst galaxies. An analysis of the turbulent and hydrostatic pressures suggest that $P_{turb}\sim P_{hydrostatic}>P_{thermal}$.
- The contribution of the WIM to the total turbulent pressure must be small. The turbulent pressure is given by, $P_{turb}\sim\sum_{i=ISMphases}(ff_v <\rho> \sigma^2)_i$, where ff_v is the volume filling factor, $<\rho>$ is the volume weighted density, and σ is the velocity dispersion in each phase. From observations of distant galaxies, we know that the molecular gas dominates the volume weighted density of the ISM.
- Using the mass surface densities of gas and stars determinations from galaxies similar or the same as the galaxies observed here (Förster Schreiber et al. 2011; Tacconi et al. 2010), we find that the galaxies generally have characteristics consistent with the Toomre Q paramater of approximately 1.

To further understand these results, we conducted 1-d simulation based on the work of Elmegreen & Burkert (2010) which is of a gas accreting disk, but now adding a prescription of the energy injection from massive stars. The results of this model suggest that indeed, the energy injection can have a substantial effect on the stability of the disk in that it can maintain the disk near Q~1 and break the equality between the gas accretion rate and the star formation rate. In other words, the disk becomes self-regulating and not solely limited or coupled to the infall rate of gas. This is because the dissipation time in these models if of-order 10 Myrs which is much shorter than the duration of the star formation in this model (and in the

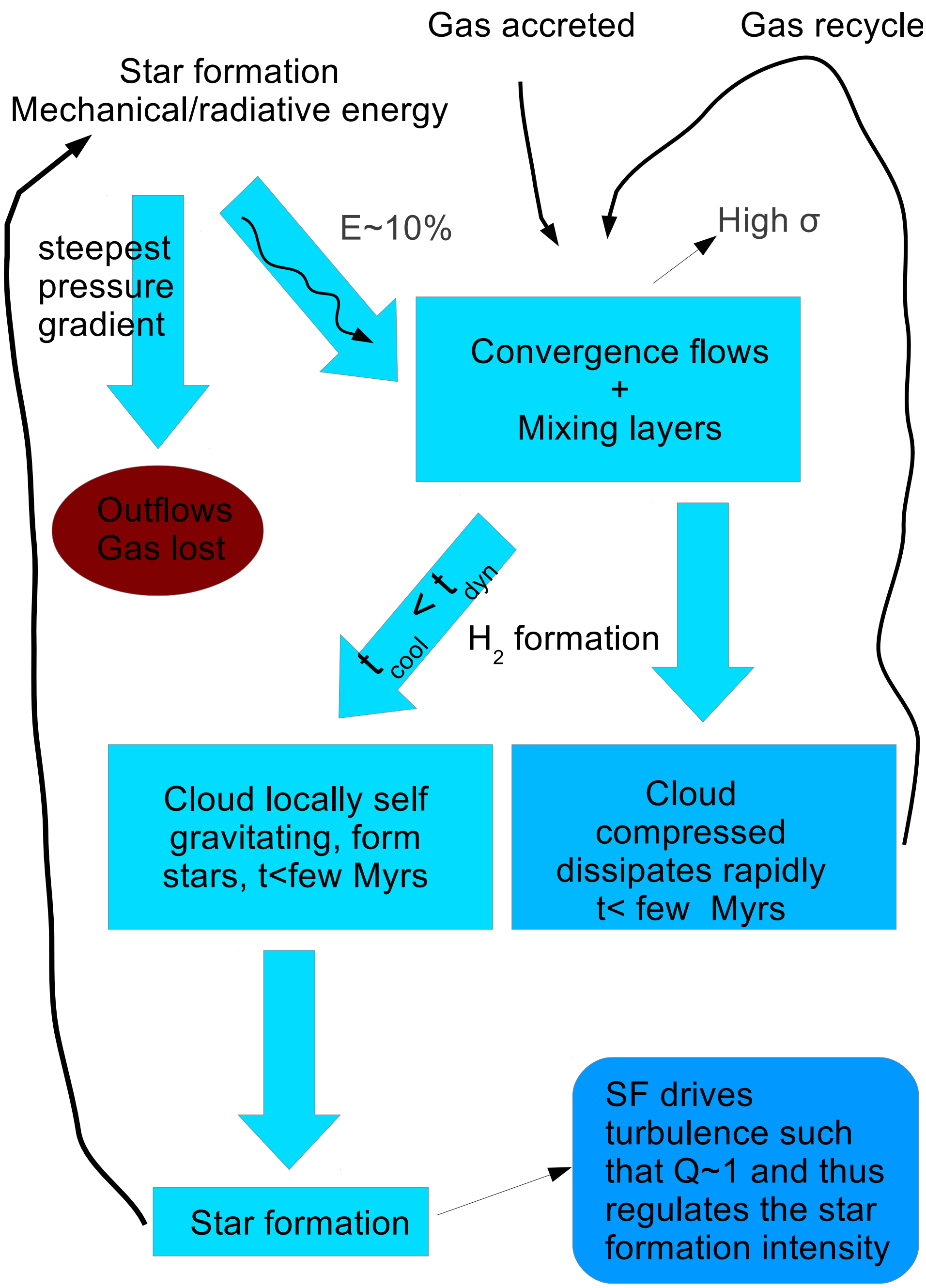

Fig. 1. The mass and energy cycle diagram outlining our hypothesis for how the mechanical and radiative energy of star formation might be captured by the molecular gas which regulates the star formation intensity of distant galaxies. The basic picture is that star formation, through the combined action of stellar winds, supernovae, and radiation pressure, drive a mass and energy flow in the ISM of distant galaxies. Since the dispersions in the gas is high, the formation of molecular gas is enhanced by the strong compression and convergence flows generated. We expect the efficiency of molecular gas formation and dissipation to be proportional to the velocity dispersion of the gas. The star formation intensities will increase until the molecular gas, which dominated the turbulent energy, until the Toomre parameter, Q, reaches about 1. Higher intensities of star formation would push Q up, stabilizing the gas and lower, would allow for greater instability pushing the intensities upwards. As the gas is consumed and lost through outflows, the coupling between the star formation and ISM would decrease, and self-regulation as we have proposed would not be able to sustain intense star formation.

observation; Erb et al. 2006; Förster Schreiber et al. 2011). However, the results that Q~1 is dependent on whether or not the turbulent pressure is high or in other words, the molecular gas has kinematics similar to (but likely less than) that observed in the WIM.

To explain the characteristics of these galaxies at high redshift, we have hypothesized that the molecular gas substantially captures the dynamics of the WIM. How might this work? We show this idea schematically in Figure 1. From observations of nearby starburst galaxies, we know that the thermal pressure in the hot X-ray emitting plasma is similar to that in the WIM. This is quite important as it suggests that the energy from the mechanical output of massive stars is being transfered into other phases and is simply not escaping from the ISM into the galaxy halo. The cooling time of the WIM is very short and gas that is shielded from the intense radiation field will become part of the warm neutral medium (WNM). However, at the high thermal pressures observed, the WNM is unstable and will quickly become part of the warm and cold molecular medium (C and WNM; Wolfire et al. 1995). Since this happens quickly, much less than an internal dynamical time, the WMN will capture (at least partially or substantially) the kinematics of the WIM. The fact of this cooling gas depends on its dissipation time of turbulence and general cooling rate. If the dissipation rate is low, the gas will not become self-gravitating and will be destroyed by the intense radiation field, heating from the surrounding medium, and from the kinematics of the ISM. However, some of the gas will dissipate its energy sufficiently quickly for the gas to become self-gravitating and collapse, fueling star formation. Since the conversion of molecular gas goes as the dispersion, this naturally sets up a self-regulation cycle which can be sustained until the gas mass surface densities drop below a critical level when the pressure can no longer couple between the efficiently phases. As the dispersion drops, so will the star formation intensity. At this point, too much of the energy output from star formation escapes the system or goes into phases will cooling times that are much too long. This leads to a nature way of reducing the star formation to intensities like those observed locally.

Acknowledgements. MDL wishes to thank the CNRS for their continuuing support.

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