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STAR FORMATION AND TURBULENT DISSIPATION IN MODELS OF DISK GALAXY EVOLUTION

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RESUMEN

La tasa de disipación de energía cinética en el MIE turbulento de las galaxias de disco es un ingrdiente clave para modelos de evolución galáctica, ya que determina la eficiencia de la retroalimentación de la formación estelar (FE) de gran escala. Con ayuda de simulaciones MHD encontramos que el MIE disipa eficientemente la energía turbulenta inyectada por fuentes de naturaleza estelar. Así, el proceso de FE puede ser auto-regulado sólo a nivel del MIE del disco. La aplicación del mecanismo de FE auto-regulada en modelos de evolución galáctica, donde los discos se forman dentro de halos de CDM en crecimiento, permite predecir la historia de FE de las galaxias de disco, incluyendo a la Vía Láctea y la vecindad solar, así como la contribución de toda la población de discos a la historia de FE cósmica. Los resultados son alentadores.

ABSTRACT

The kinetic energy dissipation rate in the turbulent ISM of disk galaxies is a key ingredient in galaxy evolution models since it determines the effectiveness of large-scale star formation (SF) feedback. Using MHD simulations, we find that the ISM dissipates efficiently the turbulent kinetic energy injected by sources of stellar nature. Thus, the SF process may be self-regulated by an energy balance only at the level of the disk ISM. The use of the self-regulation SF mechanism in galaxy evolutionary models, where disks form inside growing CDM halos, allows to predict the SF history of disk galaxies, including the Milky Way and the solar neighborhood, as well as the contribution of the whole population of disk galaxies to the cosmic SF history. The results are encouraging.

Key Words: **GALAXIES: EVOLUTION — STARS: FORMATION**

1. INTRODUCTION

Star formation (SF) and feedback are key processes in the evolution of galaxies, but probably they are the worst understood of all. The large-scale SF cycle in normal galaxies is believed to be self-regulated by a balance between the energy injection due to SF (mainly SNe) and dissipation. Two main approaches have been used to describe the SF self-regulation in models of galaxy formation and evolution: **(a)** the halo cooling flow-feedback approach (White & Frenk 1991), **(b)** the disk turbulent ISM approach (Firmani & Tutukov 1992; 1994; Dopita & Ryder 1994; Wang & Silk 1994).

According to the former, the cool gas is reheated by the "galaxy" SF feedback and driven back to the *intrahalo medium* until it again cools radiatively and collapses into the disk. This approach has been used in the semi-analytical models of galaxy formation (e.g., Kauffmann, White & Guiderdoni 1993; Cole et al. 1994). The reheating rate depends on the halo circular velocity V_c: $\dot{M}_{rh} \propto \dot{M}_s/V_c^{\alpha}$, where $\dot{M}_*$ is the SF rate (SFR) and $\alpha \geq 2$. Thus, the galaxy SFR, gas fraction and luminosity depend on V_c. In these models, the disk ISM is virtually ignored and the SN energy injection is assumed to be as efficient as to reheat the cold gas up to the virial temperature of the halo. A drawback of the model is that it predicts hot X-ray halos around disk galaxies much more luminous than observed (Benson et al. 2000).

According to approach (b), SF is triggered by gravitational instabilities (Toomre criterion) and self-regulated by a balance between energy injection and dissipation in the turbulent ISM in the direction perpendicular to the disk plane: $\gamma_{SN}\epsilon_{SN}\dot{\Sigma}_* + \dot{\Sigma}_{E,accr} = (\Sigma_g v_g^2)/(2t_{\rm d})$, where γ_{SN} and ϵ_{SN} are the kinetic energy injection efficiency of the SN into the gas and the SN energy generated per gram of gas transformed into stars, respectively, $\dot{\Sigma}_*$ is the surface SFR, $\dot{\Sigma}_{E,accr}$ is the surface mass accretion rate, and Σ_g and v_g are the gas surface density and velocity dispersion, respectively. The key parameter in this equation is the dissipation time $t_{\rm d}$. Now, the ISM is a turbulent, non-isothermal, multi-temperature flow. It is known that in the denser regions of the ISM, where stars form, the cooling time is short with respect to the dynamical times (Spitzer & Savedoff 1950; Elmegreen 1993; Vázquez-Semadeni et al. 1995, 1996). The main effect of this short cooling time is to cause the medium to behave essentially as a polytrope, with the pressure P scaling with den-

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sity ρ as $P \propto \rho^\gamma$, where γ is an effective polytropic exponent that determines the compressibility of the medium (Vázquez-Semadeni et al. 1996; Scalo et al. 1998; Spaans & Silk 2000; Jenkins & Tripp 2001). Given the medium's compressibility, the star formation rate is then determined by the mean turbulent kinetic energy (which produces the compressions), which in turn is limited by the kinetic energy dissipation rate. Therefore, the key parameter is the *turbulent* dissipation time, and a crucial question is: *how efficiently does the disk ISM dissipate the* E_k *injected by stellar sources?*.

2. TURBULENT DISSIPATION IN ISM SIMULATIONS

To explore the ISM dissipative properties, Avila-Reese & Vázquez-Semadeni (2001) used numerical MHD simulations of turbulent compressible fluids resembling the ISM of disk galaxies at the 1 kpc scale (Vázquez-Semadeni et al. 1995; Passot et al. 1995). The MHD and the internal energy conservation equations were solved in two dimensions[3] with model terms for radiative cooling and background heating. A pseudospectral method with hyperviscocity and periodic boundary conditions was used. The way in which $\mathrm{E_k}$ is injected to the fluid is crucial: it should resemble "stellar" sources like SN remnants and expanding HII regions. That is, the energy sources are discrete, generally small in comparison with the characteristic scales of the global ISM, and with filling factors typically $\ll 1$. The forcing in the simulations was generated by "winds": the gas around the SF regions received an acceleration $\mathrm{a_f}$, directed radially away, thus producing an evolving velocity profile with characteristic forcing velocity $\mathrm{u_f}$ and radius $\mathrm{l_f}$. The characteristic energy injected is: $\mathrm{e_k} \propto \mathrm{u_f a_f l_f}^2\ \Delta t_{\mathrm{OB}}$, where, Δt_{OB} is the source lifetime (assumed constant and =6.8 Myr). The two independent input parameters that define the local energy injection process are $\mathrm{l_f}$ and $\mathrm{e_k}$ (or $\mathrm{u_f}$); $\mathrm{a_f}$ is already a response of the flow. There is a third initial parameter related to the global energy injection: the surface SFR, $\dot{\Sigma}_\star$.

We performed a sizeable number of simulations to explore how the dissipative properties of the turbulent ISM depend on the forcing parameters: $\mathrm{l_f}$, $\mathrm{e_k}$, and $\dot{\Sigma}_\star$. In these simulations, the sources are placed randomly in space with a fixed probability, which determines the $\dot{\Sigma}_\star$.

The simulations show that the kinetic energy injection and dissipation rates are always very close to each other, suggesting that most of the dissipation occurs at or near the sources, where shocks are common, and that, for practical purposes, the injection and dissipation times are equal. In general, a flow with physical parameters close to the Galactic disk at the solar neighborhood dissipates its turbulent energy rapidly, in approximately 15–20 Myr. A more realistic simulation, where the SF is density directed, gives $\mathrm{t_d} \approx$ 18 Myr (in this simulation, the input sources tend to cluster due to supershell formation, see color Plate 4b). We also showed that, in terms of measurable properties of the ISM, $\mathrm{t_d}$ can be expressed as: $\mathrm{t_d} \gtrsim \langle \Sigma_{\mathrm{g}} \rangle\ \mathrm{u_{rms}}^2/(\mathrm{e_k}\ \dot{\Sigma}_\star)$, where $\langle \Sigma_{\mathrm{g}} \rangle$ is the average gas surface density, and the inequality arises because some overlapping of the forcing regions may occur. Since $\dot{\Sigma}_\star \propto \Sigma_{\mathrm{g}}{}^n$ (Schmidt law), $\mathrm{t_d} \propto \Sigma_{\mathrm{g}}{}^{(n-1)}(r)$. Thus, $\mathrm{t_d}$ is expected to decrease with Galactocentric radius.

Given the discreteness and low filling factor of the energy sources, the turbulence "propagates" away from them into the general ISM, reaching out to farther distances for lower $\mathrm{t_d}$. The velocity dispersion, $\mathrm{u_{rms}}$, of the residual turbulence is found to decay roughly inversely with distance to the source. It was also found that the dominant parameter determining $\mathrm{t_d}$ is $\mathrm{l_f}$, while the energy per source and the SFR are not very relevant ($\mathrm{t_d} \propto \mathrm{l_f}^{0.84}/(\mathrm{e_k}\ \dot{\Sigma}_\star)^{0.12}$). Thus, the production of very large active turbulent zones (able to inject energy out from the disk into the halo, for example), which occurs at large $\mathrm{t_d}$, requires large values of the source characteristic size $\mathrm{l_f}$, i.e., that the forcing regions are themselves large (supershells). These supershells could arise as a consequence of strong clustering and self-propagating SF. This might be the rule for starburst galaxies (non-stationary SF), but generally the exception in normal disk galaxies.

Our results, if applicable in the vertical direction, imply that the turbulent $\mathrm{E_k}$ produced in the disk plane is mostly dissipated inside the disk ISM. The turbulent motions will propagate up to distances close to the observed HI disk semi-thickness, and will not be able to reheat and drive back the gas into the halo. The shock-dissipated turbulent energy transforms probably into thermal energy, which could be a source of high-energy photons able to ionize the low-density extraplanar medium (up to a few kpcs from the plane).

3. THE STAR FORMATION HISTORY

A scheme of SF triggered by disk gravitational instabilities and self-regulated by the SN energy input and the turbulent energy dissipation was applied by Firmani, Hernández & Gallagher (1996) to galaxy

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[3] We argue that dissipation in 2-D is representative of that in 3-D as long as it is dominated by shocks rather than by a turbulent cascade.

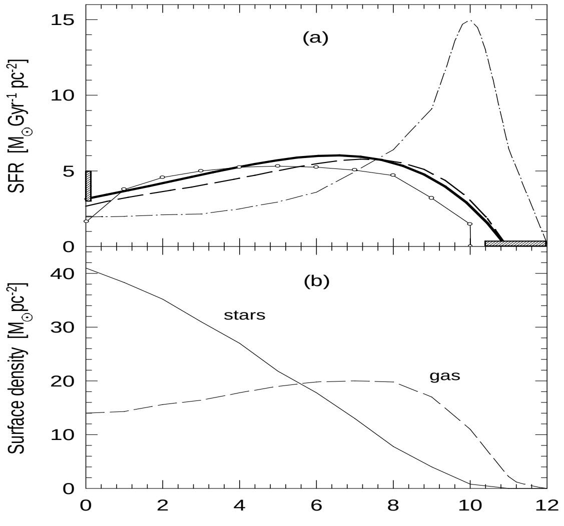

Fig. 1. *a).* SF history in the solar neighborhood: predicted by our model (thick line) and inferred from observations (jointed circles). Dashed line is for a MW model with a soft core in the halo. Dot-dashed line is the predicted gas infall rate at $R_\odot$. The vertical and horizontal shaded boxes are observational estimates for the present-day SFR and for the age of the solar neighborhood, respectively. *b).* Predicted evolution of the star (solid line) and gas (dashed line) surface densities at the solar neighborhood.

evolution models. A Schmidt law with index $\lesssim 2$ along a major portion of the disks was predicted. For closed models, even with the lowest disk surface densities, the SF timescales were shorter than 5 Gyr and the integral $(B-V)$ colors redder than 0.9. Gas infall is necessary. This infall may be provided by the cosmological mass aggregation predicted in a hierarchical CDM scenario, where disks form inside-out.

Self-consistent models of disk galaxy formation and evolution within growing CDM halos, which use the disk self-regulated SF approach, indeed predict realistic integral and radial color indices, gas fractions, surface brightness profiles as well as realistic dynamical properties and correlations among the galaxy parameters (see Firmani & Avila-Reese, this volume). In these models, the turbulent dissipation time was calculated as $\mathrm{t_d}(r) = a(2\Omega(r))/\kappa(r)^2$, where $\Omega(r)$ and $\kappa(r)$ are the angular velocity and epicyclic frequency at radius r, and a is a constant close to unity (Firmani et al. 1996). The formula above was derived from a simple dynamical analysis. The MHD simulations of the turbulent ISM presented in §2 offer the posibility to fix the value of a. Normalizing to the Galactic disk at the solar radius, we find that $a \approx 1.5-2$. The dependence of $\mathrm{t_d}$ on the radius in the formula above agrees with an inference from the simulations of such a dependence (see above).

The SF histories of most of the model galaxies have a broad maximum at $z \sim 1-2.5$, and then the SFR decays by factors of 1.5-4 until $z = 0$ (Avila-Reese & Firmani 2001). The SF history is driven by the halo angular momentum and by the halo mass aggregation history; in contrast with the halo cooling-flow model, there is no significant dependence on mass or circular velocity. The angular momentum determines the disk surface density. The higher the density, the more efficient is the SFR. The mass aggregation history determines the gas infall rate; for mass assembly histories of the halo more extended in time, the late gas accretion rate is higher, and therefore, the SFR is higher at $z \approx 0$. Thus, HSB and/or red galaxies have a maximum SFR at earlier epochs and a faster decline towards the present than LSB and/or blue galaxies. The latter may even have an increasing SFR at $z = 0$. When comparing the SFR of high-redshift disk galaxy populations with the present one, it is important to take into account these differences of the SF history on galaxy surface brightness and color and the selection effects.

3.1. *Milky Way (MW) and the solar neighborhood*

The global and local SF histories of a MW model can be predicted. For a ΛCDM cosmology, the MW model was constructed using a virial mass of 2.8 $10^{12}\mathrm{M}_\odot$, a baryon fraction of 0.02, the average halo mass aggregation history, and a spin parameter $\lambda = 0.02$. The surface brightness profiles and scale radii (bands B and K), the global gas and stellar mass fractions, and the integral colors are well reproduced (Hernández, Avila-Reese & Firmani 2001). The rotation curve decomposition is also reproduced, albeit with an excess of dark matter within the solar radius, $R_\odot = 8.5$ kpc. At $R_\odot$, the gas and stellar surface densities, as well as the $B-K$ color at the present epoch, agree rather well with observational estimates (Fig. 1b).

The present-day *global* SFR of the MW model is 2.9 $\mathrm{M}_\odot\mathrm{yr}^{-1}$; it increases slightly towards the past, attaining a maximum 9.8 Gyr ago ($z \approx 1.3$). The *local* surface SFH at $R_\odot$ is shown in Figure 1a (thick solid line, in units of $\mathrm{M}_\odot\mathrm{yr}^{-1}$ pc^{-2}). It starts to increase 11 Gyr ago (roughly when the disk forms at this radius), attains a maximum $\sim 6-7$ Gyr ago, and then decreases by a factor of two at the present epoch. By using a sample of field stars from the Hipparcos catalogue and comparing it with synthetic colour-magnitude diagrams, the SFR per unit of volume at $R_\odot$ was inferred by Bertelli & Nasi (2001). Hernández et al. (2001) converted this SFR to a surface SFR (open circles in Fig. 1a). The agreement between observations and model is encouraging. The introduction of a soft core in the CDM halo (to better fit the observed rotation curve) does not influence significantly the predicted SFR history (dashed line in Fig. 1a). We notice that the observational inference describes only the general trend of the SFH over the total life of the system, and not its detailed shape, which may be discontinuous. The model results were smoothed in time to facilitate the comparison. Interactions with satellites can introduce bursts of SF (e.g., Rocha-Pinto, Maciel & Scalo 2000; Kauffmann, Charlot & Balogh 2000).

3.2. *Integral disk population SF history*

Figure 2 reproduces a compilation of data for the integral SFR in the universe at different redshifts presented by Kravtsov & Yepes (2000). In this Fig., the integral SF history due to only (model) disks is also shown (thick dashed line). At low redshifts the observed SFR decreases more rapidly than models. Models give actually an upper limit for the disk contribution to the cosmic SF history, because they do not take into account neither the truncation of the gas infall in the massive galaxies due to large gas cooling times and/or external factors, nor the fact that at late epochs some of the disk accreting material might already be in form of stars (satellite or companion galaxies). At $z \gtrsim 2$, most of the data collected by Kravtsov & Yepes, as well as more recent estimates (e.g., Nandra et al. 2002; shaded rectangle), show that the SFR remains roughly constant, while the (model) disk contribution decreases. A recent re-analysis of the *HST* deep field by Lanzetta et al. (2002) shows that the SFR *even increases significantly* at redshifts larger than 2. The model disk galaxy population (ΛCDM cosmology) seems to be able to explain the observed cosmic SF history inferences up to $z \approx 2$, modulo the strong fall since $z \approx 0.5$. At epochs earlier than $z \approx 2$, the contribution of disk galaxies to the cosmic SFR slightly and continuosly decreases.

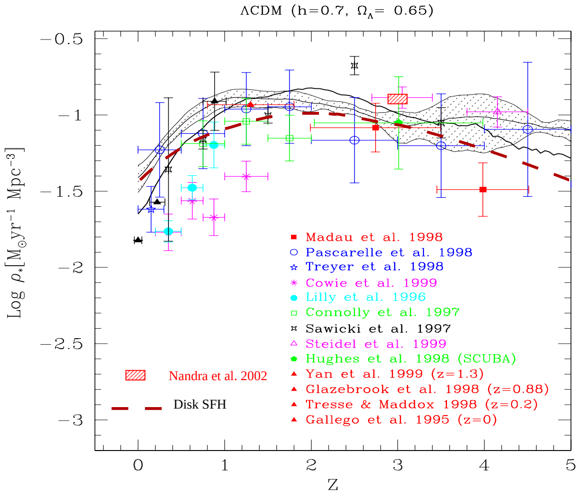

Fig. 2. Dust corrected estimates of the cosmic SFR at different redshifts (points) from UV and Hα observations as collected by Kravtsov & Yepes (2000), and from X-ray observations of $z \sim 3$ LBGs. The data points have been converted to the ΛCDM cosmology. Dashed region is from the Kravtsov & Yepes gasdynamical simulations, while the dashed solid line is our model estimate of the contribution to the cosmic SF history by stars formed in the disks (the ΛCDM model was used).

4. CONCLUSIONS

The SF process is a key ingredient for models of galaxy formation and evolution. For disk galaxies, stationary (non-bursting) and self-regulated SF seems to be a reasonable description. In this description, the large-scale SF is triggered by gravitational instabilities of the gaseous disk (Toomre criterion) and self-regulated by an energy balance in the ISM perpendicular to the disk plane. The key factor in this energy balance is the ability of the turbulent ISM to dissipate the kinetic energy; the turbulent dissipation time determines the effectiveness of large-scale SF feedback.

Our MHD, nonisothermal simulations of the ISM including realistic, stellar-like forcing, show that turbulent energy is dissipated rapidly, mostly at or near the sources, where shocks are common. The dissipation time $\mathrm{t_d}$ is found to increase with the forcing scale $\mathrm{l_f}$ and depends only very weakly on $\mathrm{e_k}$ and $\dot{\Sigma}_\star$. For properties of the ISM close to those at the solar neighborhood, $\mathrm{t_d} \approx 15 - 20$ Myr. Forced and decaying turbulent regimes coexist within the same flow. The rms velocity dispersion of the "residual" turbulence decays roughly inversely with distance from the injection sources. Turbulent motions produced near the disk plane will propagate only to distances of the order of the observed HI disk semi-thickness. This is consistent with the disk self-regulated SF scheme mentioned above, where the HI thickness results from the balance between kinetic energy injection and its dissipation rate.

The application of this scheme to self-consistent models of disk galaxy formation and evolution within growing ΛCDM halos leads to rather succesful predictions for the SFR, surface brightness, and color radial profiles of the disk galaxy population. The main drivers of the SF history are both the gas infall

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rate determined by the cosmological mass aggregation rate, and the disk surface density determined by the halo angular momentum. The SFR depends very weakly on mass. The SF history predicted for the solar neighborhood is in excellent agreement with observational inferences. The predicted integral disk SF history describes well the observed cosmic SF history until $z = 2 - 3$. At earlier epochs, the disk population SFR decreases while the observations show that the cosmic SFR remains constant or even increases, suggesting that at early epochs most of the UV and X-ray radiation is not produced by SF in disks.

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