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Editors: Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen

STAR FORMATION THRESHOLDS AND GALAXY EDGES

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RESUMEN

La existencia de un umbral en la densidad superficial para la formación estelar se explica habitualmente en términos del criterio de Toomre para la inestabilidad gravitacional en un disco delgado en rotación. Aquí mostramos que no es la inestabilidad gravitacional la que causa la formación de la fase molecular fría, sino viceversa: la transición de la fase interestelar caliente ($T \sim 10^4$ K) a la fría ($T < 10^3$ K) causa que el disco se vuelva inestable gravitacionalmente. La rotación no afecta la densidad superficial crítica a la cual ocurre la transición de fase, y no puede estabilizar la fase fría en el disco exterior.

ABSTRACT

The existence of a surface density threshold for star formation is usually explained in terms of the Toomre criterion for gravitational instability in a thin, rotating disk. Here it is shown that it is not gravitational instability that causes the formation of a cold, molecular phase, but vice versa: the transition from the warm ($T \sim 10^4$ K) to the cold ($T < 10^3$ K) interstellar phase causes the disk to become gravitationally unstable. Rotation does not affect the critical surface density at which the phase transition occurs and cannot stabilize the cold phase in the outer disk.

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

1. INTRODUCTION

Stellar disks are finite: the surface brightness distribution of spiral galaxies is observed to cut off beyond a few disk scale lengths (van der Kruit 1979). The fact that gas disks typically extend beyond the stellar disk suggests that the radial truncation of the stellar luminosity profile is due to a star formation threshold. Indeed, measurements of the distribution of Hα emission show that the (azimuthally averaged) star formation rate also drops abruptly at a finite radius (Kennicutt 1989).

The existence of a (global) surface density threshold for star formation is usually explained in terms of the Toomre criterion for gravitational instability (Spitzer 1968). Neither rotation nor pressure can stabilize a thin, gaseous, differentially rotating disk if the Toomre Q parameter,

$$Q(r) \equiv \frac{c_s \kappa}{\pi G \Sigma_g}, \tag{1}$$

is less than unity (Toomre 1964); where the effective sound speed c_s, the epicyclic frequency κ, and the gas surface density Σ_g all depend on radius r.

Here, it is proposed that the velocity dispersion is critical to the star formation threshold. Since stars form from molecular hydrogen, a cold ISM phase is a necessary ingredient for star formation. The cold phase has a temperature that is roughly two orders of magnitude lower than that of the warm phase ($T \sim 10^2$ K vs. 10^4 K), and thus a thermal velocity dispersion that is smaller by a factor 10. Consequently, when the surface density exceeds the critical value for the existence of a cold phase, a significant fraction of the gas will find itself with a velocity dispersion, and thus a Q-parameter, that is much smaller than that of the warm phase.

This work is described in more detail in Schaye (2002).

2. RESULTS

To test the hypothesis that the transition to the cold phase causes the disk to become gravitationally unstable, a model was constructed of a gaseous, exponential disk embedded in a dark halo. The disk is self-gravitating, contains metals and dust, and is illuminated by UV radiation. A detailed description of the model can be found in Schaye (2002).

The solid curves in figure 1 show the Toomre Q-parameter as a function of radius for a typical high surface brightness (model HSB, left panel, $v_{\max} = 218\ \mathrm{km\,s^{-1}}$, $R_d = 4.7$ kpc) and a typical low surface brightness galaxy (model LSB, right panel, $v_{\max} = 72\ \mathrm{km\,s^{-1}}$, $R_d = 3.9$ kpc). At the critical radius r_c the Q-parameters drop sharply from $Q > 2$ at $r > r_c$ to values smaller than unity at $r < r_c$. This sudden decrease is associated with a similar drop in

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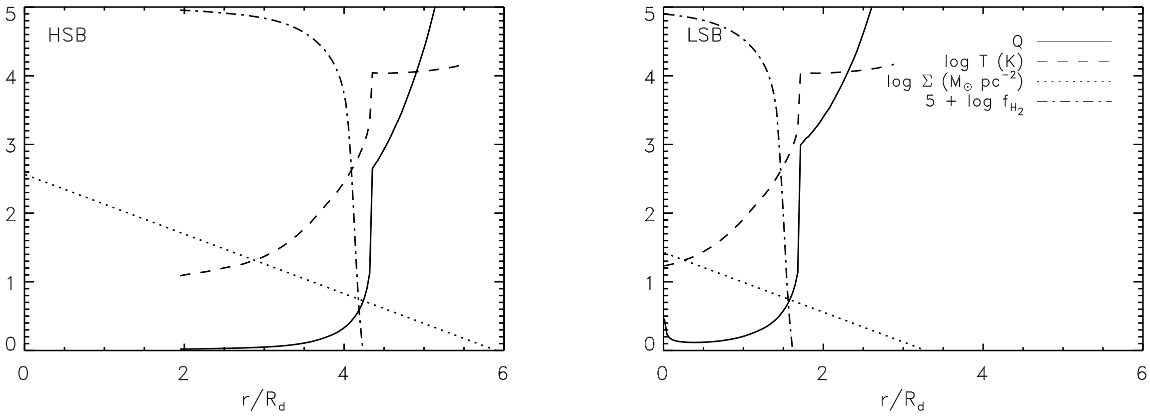

Fig. 1. The Toomre Q parameter (solid), the temperature $\log T$ (dashed), the molecular fraction $5 + \log f_{H_2}$ (dot-dashed), and the surface density $\log \Sigma(\mathrm{M}_\odot\,\mathrm{pc}^{-2})$ (dotted) are all plotted as a function of radius for models HSB (left panel) and LSB (right panel). The sudden drop in the Q-value coincides with (and is caused by) a similar drop in the temperature, and a sharp increase in the molecular fraction. The transition to the cold phase, which coincides with the onset of gravitational instability ($Q < 1$), occurs at the same surface density in the two models. Note that the models become unrealistic shortwards of the critical radius, where feedback from star formation will increase the UV field, the metallicity, and the turbulent pressure.

the temperature (dashed curves) from $T \approx 10^4$ K to $< 10^3$ K and with a sharp increase in the molecular hydrogen fraction (the dot-dashed lines show $5 + \log f_{H_2}$) from $f_{H_2} \ll 10^{-3}$ to $> 10^{-3}$.

The fact that Q is significantly greater than unity for $r > r_c$ and then drops sharply to $Q < 1$ at $r \approx r_c$ implies that it is the transition to the cold phase that causes the Toomre instability and not vice versa. Note that since both the surface density (dotted lines) and the epicycle frequency (not plotted) vary smoothly across r_c, it must be the decrease in the sound speed associated with the phase transition that causes the drop in Q.

The transition to the cold phase is sharp because the gas is thermally unstable at intermediate temperatures and because both self-shielding and the formation of molecular hydrogen provide positive feedback loops. Galactic rotation does not affect the critical surface density at which the phase transition occurs ($\log N_{H,\mathrm{crit}} \sim 20.75$ cm^{-2}, $\log \Sigma_g \sim 0.77$ M$_\odot$ pc^{-2}, see Schaye 2002) and cannot stabilize the cold phase in the outer disk.

Since rotation is generally unimportant, star formation thresholds are a local phenomenon: peaks in the surface density that exceed the threshold value will form stars regardless of their position in the disk. Thus, star formation beyond r_c is possible, in particular in spiral arms. Compared to HSB galaxies, LSB galaxies have low star formation efficiencies because their (azimuthally averaged) surface densities become subcritical at smaller radii relative to their disk scale lengths.

Although the identification of the critical radius for star formation with the transition to the cold phase is robust, the detailed predictions of the models may be unrealistic for $r < r_c$. The model effectively predicts its own demise: within the critical radius feedback from star formation will modify the thermal and ionization structure of the disk and will generate turbulence, possibly leading to self-regulation of the star formation rate such that $Q \approx 1$. However, we emphasize that the prediction of widespread star formation at $r < r_c$ is robust, since the conditions that invalidate the model are *consequences* of this prediction.

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