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STAR FORMATION IN AN UNSTABLE INTERSTELLAR MEDIUM

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RESUMEN

Se discuten densidades de columna críticas para inestabilidades gravitacionales y para enfriamiento a temperaturas de nubes difusas. La escala fundamental para la formación de estrellas en las regiones externas de las galaxias, en los brazos en espiral y en los anillos de resonancia parecen estar siempre relacionados con la longitud de la inestabilidad local. En brazos espirales y anillos, este largo es proporcional al grosor del brazo o anillo en el umbral de inestabilidad. El modelo de inestabilidad produce una tasa de formación estelar proporcional a la potencia 1.5 de la densidad, y el tiempo de consumo de gas es inversamente proporcional a la potencia 0.5 de la densidad. Debido a que la densidad de gas crítica para el colapso se escala directamente con la densidad local en todas sus formas, la tasa de formación estelar es mucho mayor en las zonas internas de las galaxias y el tiempo del consumo de gas es mucho menor, una vez que el umbral es excedido. Esto implica que, en las regiones internas de las galaxias, las estrellas se forman en brotes, mientras que el disco principal puede ser relativamente estable en fracciones grandes del tiempo de Hubble. La naturaleza de tipo brote en la formación estelar de galaxias enanas probablemente no está relacionada con el consumo de gas sino con la pérdida del gas debido al bajo pozo de potencial cerca de la región de formación estelar. Así, hay dos causas para los brotes estelares.

ABSTRACT

Critical column densities for gravitational instabilities and for cooling to diffuse cloud temperatures are discussed. The fundamental scale for star formation in the outer regions of galaxies, in spiral arms, and in resonance rings seems to be always related to the local unstable length. In spiral arms and rings, this length is proportional to the arm or ring thickness at the threshold of instability. The instability model gives a star formation rate proportional to the 1.5 power of the density, and a gas consumption time inversely proportional to the 0.5 power of the density. Because the critical gas density for collapse scales directly with the local density in all forms, the star formation rate is much higher in the inner regions of galaxies, and the gas consumption time much smaller, once the threshold is exceeded. This implies that the inner regions of galaxies usually form stars in bursts, while the main disks can be more-or-less steady for a large fraction of the Hubble time. The burst-like nature of star formation in dwarf galaxies is probably not related to gas consumption, however, but to gas clearing from the low potential well near the star formation region. Thus there are two reasons for starbursts.

Key words: **STARS: FORMATION — GALAXIES: SPIRAL — GALAXIES: STARBURST — INSTABILITIES**

1. AVERAGE DYNAMICAL NEAR-STABILITY

The interstellar medium in normal galaxies is mostly stable. The average gas density is slightly less than the critical tidal density; the shear rate, self-gravity rate and cooling rate are all about the same, and the stability parameter Q is about unity (Kennicutt 1989), meaning that there is a balance between rotation and self-gravity. This state of near-stability is presumably the result of star-formation feedback (e.g., Franco & Cox 1983) in which excess star formation leads to heating, a thicker ISM, lower density, and then less star formation.

2. THERMAL STATES OF GAS

Low surface density regions such as outer disks, low surface brightness galaxies, and some regions of dwarf galaxies, may have extra stability because of an inability to reach cool, diffuse-cloud temperatures (Elmegreen & Parravano 1994). When the surface density σ is low, the pressure is low, scaling approximately as σ^2, and in these regions the radiation field is often not particularly low, scaling only as σ. Then there is ample photoelectric heating for the gas but significantly less cooling at the lower density (from the lower pressure), and only the warm phase at several thousand degrees (i.e., the "not strongly absorbing" neutral medium) can exist in equilibrium. Such an ISM should be very different from that near the Sun. It is very difficult to make cold gas (10 K) when cool gas (100 K) is rare, and cold gas is a necessary precursor to normal star formation. In cold gas the density can be high at the local pressure and then self-gravity can be strong enough to make the gas collapse.

3. CRITICAL COLUMN DENSITIES

There are two conditions for star formation to proceed by normal routes at normal rates: (1) self-gravity is stronger than dynamical forces from galactic tides, shear, and rotation, and (2) the pressure is high enough to support cool gas in thermal equilibrium. These conditions can be written in terms of critical column densities, the first depending on the velocity dispersion and epicyclic frequency, and the second on the local radiation field. For the first we have the usual condition from the Toomre stability analysis:

$$\sigma > \sigma_{\rm crit,grav} \sim \frac{\kappa c}{\pi G}, \tag{1}$$

where κ is the epicyclic frequency and c is the turbulent speed multiplied by the square root of the effective ratio of specific heats, which is probably about 0.3 (see Elmegreen 1991, 1994a). For the second condition we have

$$\sigma > \sigma_{\rm crit,heat} \sim 7 \left(\frac{f}{\theta}\right)^{0.5} \left(\frac{G_{\rm uv}}{G_\odot}\right)^{0.6} M_\odot\ {\rm pc}^{-2}, \tag{2}$$

where f is the ratio of the gas surface density σ to the total surface density $\sigma_{\rm T}$ of gas plus stars in the gas layer; θ is the average ratio of the thermal pressure to the total pressure in the ISM, and $G_{\rm uv}$ is the ambient radiation field, normalized to the solar value $G_\odot$. This expression comes from a power-law fit to $P_{\rm min}$ in figure 2 of Elmegreen & Parravano (1994) and from the expression for total pressure, $P = (\pi/2)G\sigma\sigma_{\rm T}$ derived in Elmegreen (1989). A numerical evaluation might use $f = 0.2$ and $\theta = 0.2$, in which case $f/\theta \sim 1$.

4. SMALL PERTURBATIONS TO STABILITY

Random density fluctuations from the cloudy/turbulent distribution of gas in the ISM, in spiral arms, and in gas rings at spiral or bar resonances (i.e., the outer Lindblad resonance of the spiral or the inner Lindblad resonance of the bar) can lead to conditions in which self-gravity overcomes the usual resistance to collapse from pressure, rotation, and shear. Then large regions of the ISM can collapse into giant cloud complexes, which, after further energy dissipation and collapse, can form dense molecular clouds and stars. The final result of this collapse is the formation of a star complex (Efremov 1995) that is a composite of several OB associations with an age range up to 50 million years. Gould's Belt is an example of a star complex for a normal disk in a galaxy the size of ours, as is the pattern of beads-on-a-string for star formation in normal spiral arms. The hot spots in nuclear ILR rings are another example. These regions seem to form stars by the same physical process: gravitational collapse of the ambient ISM forming a Jeans-mass cloud with star and cluster formation in the dense cores.

4.1. Random Density Fluctuations and Complex Sizes

The giant patches of star formation that are visible in the outer parts of galaxies probably form by the gravitational collapse of disk gas in conditions of marginal instability. Sometimes these patches get distorted by shear and then look like small spiral arms. The typical size of the largest star formation patch in a galaxy is found to be always about 1/2 the length of the fastest growing instability (Elmegreen et al. 1994), as expected from the instability model. This fastest growing length is

$$\lambda_{\rm peak} = \frac{2c^2}{G\sigma}, \tag{3}$$

but a more illustrative expression substitutes Q for σ from the definition of $Q = \kappa c/(\pi G \sigma)$. Then we get

$$\lambda_{\rm peak} = \frac{2\pi c Q}{\kappa}. \quad (4)$$

Now it can be seen that because $cQ \sim$ constant for normal galaxies, c because most turbulent speeds are around 5 or 10 km s^{-1} (if the galaxy is not interacting) and Q because of feedback, the size of a complex should scale inversely with the epicyclic frequency (Elmegreen et al. 1994, 1995a). The epicyclic frequency varies from galaxy to galaxy approximately as V/R for rotation speed V and size R, and this gives the interesting result that the ratio of the largest complex size to the galaxy size varies inversely with galaxy rotation speed. These results are found to apply to a wide range of galaxy masses, spanning 11 magnitudes of absolute brightness (Elmegreen et al. 1995).

4.2. Spiral Arms

Star formation often takes the form of giant complexes spaced out somewhat uniformly along spiral arms. The separation between these complexes is about the Jeans length so one explanation for this effect is that the gas in the spiral arms is gravitationally unstable to collapse along the length of the arms. A stability analysis including low spiral arm shear and magnetic forces (Elmegreen 1994a) gives a separation

$$\lambda_{\rm sep} \sim \frac{\pi}{X} \times \text{Arm Thickness}, \quad (5)$$

where $X = Rk_{\rm J}$ for arm half-thickness R and characteristic Jeans wave number $k_{\rm J} = (2\pi G \rho_{\rm s})^{1/2}/c$ for arm-center density $\rho_{\rm s}$. This dimensionless parameter X can also be written $(2G\mu_{\rm s})^{1/2}/c$ with mass per unit length along the arm $\mu_{\rm s} = \rho_{\rm s}\pi R^2$. X determines the degree of self-gravity of the arm: $X > 1$ for an arm that is strongly self-gravitating. When $X > 1$, the fastest growing wavelength is given by $2\pi/k_{\rm J}$, from which the above equation for $\lambda_{\rm sep}$ follows.

What is important about this expression for $\lambda_{\rm sep}$ is that at the threshold of instability, where $X \sim 1$, the separation between cloud complexes or star complexes along an arm is always about three times the arm thickness, which was an observational result found earlier (Elmegreen & Elmegreen 1983). The separation therefore depends more on the geometry of the gas than on the conventional Jeans length. Separations are about constant with radius in a galaxy, even though the 2D Jeans length given in the previous section, $2c^2/G\sigma$, should increase exponentially with radius in a disk as the mass column density σ decreases exponentially. The constant separation that is actually observed in galaxies results from the near-constant arm thickness over the main disk, and this is the result of the increasing spiral arm strength with radius, giving more non-linear arm profiles at larger radii, with relatively wider interarm regions and narrower arms.

Another condition for the formation of giant complexes in spiral arms is that the gas has time to collapse before it flows out of the arms. This condition can be written in a simple form for $X \geq 1$ midway in the disk and is approximately (Elmegreen 1994a)

$$\rho_{\rm s} > \rho_{\rm crit,ave} \quad (6)$$

for average critical density $\rho_{\rm crit,ave} = \rho_{\rm ave} Q_{\rm ave}$ at that radius in the disk, evaluated by ignoring the spiral. This condition implies that if the spiral arm surface density exceeds the critical value determined in the absence of the spiral, then the gas in the arm can collapse gravitationally before it flows out. The result is significant star formation in the arms by the formation of giant complexes. But note that the active parts of most galaxies have even the average column density above the critical value (Kennicutt 1989), so star formation would occur there by these same processes anyway, even without a spiral. This explains why the total star formation rate per unit area in the optical parts of galaxies is always about the same, regardless of the presence or lack of spiral arms (see reviews in Elmegreen 1987, 1995).

In a region where the average surface density is subcritical, as in the outer parts of a disk (where the exponential decrease of σ eventually overcomes the $1/r$ decrease of κ in the expression for $Q = \kappa c/\pi G \sigma$), spiral arms can increase the surface density to above the critical value and trigger star formation where none would have occurred otherwise.

It follows from this discussion that star formation slows significantly in the outer parts of galaxies for three reasons: (1) $\sigma < \sigma_{\rm crit,grav}$, (2) $\sigma < \sigma_{\rm crit,heat}$, and (3) there are no strong spirals because the outer disk is beyond the outer Lindblad resonance for the main spiral arm system. This OLR typically occurs at about R_{25} (Elmegreen & Elmegreen 1995), which is about four disk scale lengths.

4.3. Resonance Rings

Star formation is often enhanced in circumnuclear rings that are located at or close to the inner Lindblad resonance of a bar or ovally distorted galaxy. At this resonance, the epicyclic motion of a star carries it over one complete oscillation in the time it takes to go from one side to the other of the bar. The ring forms because gas accretes inward along the bar, losing its angular momentum via bar torques, and then stalls at the ILR because the torques change sign. Gas accretion increases the ring density until a critical value is reached, after which star formation begins by the gravitational collapse of ring gas.

The critical value of the ring density for collapse is about $0.6\kappa^2/G$ (Elmegreen 1994b) for epicyclic frequency κ. This threshold is analogous to $\sigma_{\rm crit,grav}$ if we convert density to column density, $\rho = \sigma/2H$, using the scale height $H = c^2/(\pi G\sigma)$. When the ring collapses it makes several giant cloud complexes along the circumference, and these complexes collapse further to make bright star formation centers which are sometimes called hotspots for these galaxies (Pastoriza 1975). The star formation rate is very rapid, giving a starburst, because the critical density is very high. This critical density is high because κ is high in the inner regions of galaxies, scaling approximately as $1/r$ for galactocentric radius r.

If we assume the star formation rate per unit volume is proportional to the mass per unit volume times the rate at which the gas collapses, we get a Schmidt-type star formation law with a rate proportional to $\rho^{1.5}$. Since $\rho > \kappa^2/G$ at the time of star formation and $\kappa \sim 1/r$, the star formation rate per unit volume scales approximately with $1/r^3$. Thus the star formation rate per unit volume can be 1000 times higher in a 500 pc ring than in the main disk of a galaxy, at 5 kpc. By a similar argument, the gas consumption time scales with the inverse of the collapse rate, which is proportional to $\rho^{-0.5} \propto r$. In the inner regions of a galaxy, r is small and the gas consumption time can be smaller than in the main disk by a factor of 10 or more.

From these considerations it is now evident why star formation can be more-or-less steady in the main disks of galaxies, and why it is usually burst-like in the center. The average density is low in the main disk so the star formation rate is modest and the gas consumption time long. Thus star formation stays at a near-steady rate without severe gas depletion. On the other hand, the density is very high in the center once star formation begins, and the gas consumption time is very short, so star formation is extremely intense and short-lived there.

The separation between hotspots follows from the instability model. It is essentially the wavelength of the fastest growing mode. This wavelength scales with the ring thickness, just as the separation between complexes in a spiral arm scales with the arm thickness. At the threshold for collapse, where the density exceeds the critical value κ^2/G and also $G\mu/c^2 \sim 1$ for mass per unit length μ along the ring, the separation between complexes is about four times the ring thickness. This gives about four complexes in a ring whose thickness is 1/3 of its radius. If $G\mu/c^2$ is larger than one, then more than four hotspots will form. Note that when $G\mu/c^2 = 1$ and $\rho = 0.6\kappa^2/G$, the velocity dispersion of the gas is $c \sim R\kappa e/2 \sim 0.4\ V_{\rm rot}$ for ring thickness equal to $r/3$. This is a relatively high dispersion, corresponding to a thick ring.

5. LARGE PERTURBATIONS TO STABILITY

Galaxy interactions or mergers can lead to high velocity flows inside the combined systems, and this can lead to strong shocks and very high gas densities over large regions. The shock fronts are probably shaped like spiral arms, namely, long in one dimension and thin in two dimensions, so an important condition for instability in the compressed region is $G\mu/c^2 > 1$ for mass/length μ and velocity dispersion c. The velocity dispersion in the shock should probably be high also. The important point is that the density is extremely high throughout a large region, probably greatly exceeding the threshold for collapse, so star formation should be very rapid in the compressed region, possibly forming a full Jeans mass of stars, $10^7 M_\odot$ or more, at high efficiency in only 10^7 years, which is several times the collapse time. The efficiency can be high when the velocity dispersion is high because then the clouds that form, which also have high virial velocities, are not easily broken apart by internal star formation (Elmegreen, Kaufman, & Thomasson 1993).

6. TWO KINDS OF STARBURSTS

Starbursts in nuclear regions are probably the result of normal star formation processes at very high densities. The burst occurs because the gas consumption time is short, as discussed above. In dwarf galaxies the density is not particularly large so the gas consumption time should not be short. Indeed, dwarf irregulars typically have a very high gas fraction even if there is a burst in one region. Thus star formation may not end because of gas exhaustion, but because of gas expulsion from the immediate neighborhood of the star formation.

In dwarfs, the binding energy is very low: rotation or turbulent speeds can be 50 km s^{-1} or less. The gas in the region of star formation should be easily removed from the shallow potential well, and then star formation will stop (e.g., Marlowe et al. 1995). This is a different reason for a burst than in nuclear regions of large spiral galaxies where the total density is high. The gas would not generally be removed from the whole dwarf galaxy because the high pressure from the star formation event cannot travel very far along the dense midplane: it all vents to the halo where it probably compresses the residual dwarf gas from above and below.

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