Triggering of Cloud Collapse in a Galactic Disk by Infall of a High Velocity Cloud

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ABSTRACT

We have expressed in linearized form the five classical coupled equations representing the rotating gas disk of a standard disk galaxy. We solve them in three limiting cases for the gas disk:1) Infinite thickness and uniform rotation, 2) Finite thickness and uniform rotation, and 3) Infinite thickness and shearing box approximating differential rotation. We then tested the effect of a giant high velocity cloud (HVC) colliding with the disk at velocities in excess of 100 km s^{-1}. We find that the usual Jeans criterion for the limit of cloud stability is modified by the additional term arising from the effect of the HVC collision with the gas disk. This term, which contains the velocity of the incoming cloud, and a characteristic scale for the shock front, is closely comparable in magnitude to the original term (the square of the product of the sound speed and the characteristic wave number) in the static Jeans equation and also similar in magnitude to the global effect of shear. This result shows that an HVC falling onto a disk which contains clouds close to Jeans equilibrium will be generally effective in triggering cloud collapse and subsequent star formation.

key words: Galaxies: kinematics and dynamics

1. Introduction

In the context of standard Λ-CDM cosmology the accumulation of matter to form galaxies by progressive accretion is nowadays considered standard (Klypin et al. 2002, Salucci et al. 2003). Emphasis has consistently been placed on the formation of sub-galactic units of stars which go on to coalesce into larger galaxies and on the absorption of minor, satellite, galaxies by large galaxies (Hernandez & Lee 2004). For entirely understandable observational reasons much less attention has been paid to the evolution of galaxies via secular gas accretion. There is no reason to assume, however, the absence of relatively large numbers of gas clouds at the low mass end of the mass function of galaxy scale clouds, too small to convert a significant fraction of their masses into stars, which would be available within groups of galaxies to fuel the secular evolution of larger galaxies by accretion. There is in fact major support for an infall scenario as an essential element in the chemical evolution of galaxies. Within the Galaxy the classical "G-dwarf problem" (van den Bergh 1962, Schmidt 1963, Tinsley 1977), the difficulty of explaining the dearth of low metallicity stars in the solar neighborhood, is best explained by infall of low metallicity gas to the disk throughout its lifetime, (see Clayton 1984, 1988, Toth and Ostriker 1992, Chiappini et al. 1997, Casuso & Beckman 1997, 2001, Takeuchi & Hirashita 2000). More recently this scenario has been strengthened by observations of the metallicity distribution of local K-dwarfs, which are less affected than G-dwarfs by evolution away from the main sequence, (Favata et al. 1997, Kotoneva et al. 2002, Casuso & Beckman 2004), and which are modelled very well using the infall hypothesis. Studies of integrated light from stellar populations in external galaxies suggests that the phenomenon is in no way restricted to the Galaxy (Worthey et al. 1996, Espana & Worthey 2002, Bellazzini et al. 2003). A steady supply of low metallicity gas can explain the virtually constant metallicity of the disk stars formed during the past 5 Gyr (Meusinger et al. 1991, Edvardsson et al. 1993, Feltzing et al. 2001), as well as the virtually constant SFR, averaged in bins of Gyr. In fact the SFR has even shown a tendency to rise (Rocha-Pinto et al. 2000) which is very hared to explain without gas infall. Current chemical evolution models for the solar cylinder which explain well the time evolution of most metals, and specifically that of the light elements, give an average total accretion rate for the Galaxy of $\sim$2 $M_\odot$ yr^{-1} (see e.g. Casuso & Beckman 2001), while estimates of the SNII rates in the Galaxy (Dragicevich et al. 1999) are consistent with a gas arrival rate of a few $M_\odot$ yr^{-1}.

Although as we have seen there is considerable indirect evidence for gas infall, notably in the Galaxy but also in nearby external galaxies, direct evidence is harder to establish. Detection techniques for HI are only now reaching the sensitivities to detect clouds with HI masses much below 10^8 $M_\odot$ falling onto external galaxies. For the Galaxy the situation is more favourable. In 1963 Muller, Oort and Raimond (Muller et al. 1963) discovered the High Velocity Clouds (HVC's) of neutral atomic hydrogen having velocities which differ from those of projected Galactic rotation by up to several hundred km s^{-1}. The results of accumulated observational research on HVC's can be found in Wakker & van Woerden (1997) and a recent, representative major observational effort on southern HVC's in Putman et al. (2002). As early as 1966, Oort (1966) suggested that these HVC's may be essentially Local Group members (see also Verschuur 1969, Oort 1970), i.e. not gravitationally bound to the Galaxy, but to the Local Group of galaxies, using the argument that velocities relative to the Galactic plane greater than the escape velocity could best be explained this way. Although many workers have preferred to consider them as recycled gas ejected from the Galaxy and falling back (the "Galactic Fountain") (see e.g. de Avillez 2000) the idea that at least a fraction of the HVC's are Local Group members has received considerable support, both observational and theoretical. Among the arguments supporting a Local Group origin are the low measured metallicities of specific clouds (see Wakker et al. 1999 a, b), the symmetry of the velocity distribution about the Local Group barycentre (Blitz et al. 1999) and mutually consistent estimates of the integrated mass of the HVC's and the "missing" dynamical mass of the Local Group (Lopez-Corredoira et al. 1999). Wakker et al. (1999 a, b) have computed net infall rates for HVC gas to the Galactic plane. They used the velocity component of an HVC towards the plane, and the estimated mass and distance, and then integrated over the subset of HVC's deemed to be truly extragalactic. Distance uncertainty leads to a large uncertainty in the overall result, but the ranged derived, between 0.5 $M_\odot$ yr^{-1} and 5 $M_\odot$ yr^{-1}, spans the estimated values from the SNII rate and from chemical modelling detailed above. Lepine and Duvert (1994) modelled numerically the star forming impact of an HVC falling onto a galactic gas disk, with specific reference to the production of the local OB associations in Gould's belt. Their simplified dynamical treatment showed the importance of understanding the effects on star formation of a large gas cloud falling onto a typical galactic disk. Maller & Bullock (2004) developed an scenario where galaxy formation is fuelled by the infall of pressure-supported clouds. So they explain naturally the baryonic mass of the Milky Way galaxy, expecting clouds in galactic haloes to be $\sim$1kpc in size and to extend $\sim$150kpc from galactic centres. In this paper we attempt something which less ambitious but more general. We aim to make sufficient simplification in the equations describing the interaction of an HVC with a quiescent gas disk in rotation to allow us to obtain an analytical solution. We will then use this to explore how the impact of an HVC affects the underlying gravitation equilibrium of the clouds and thereby can trigger their collapse prior to the star forming process.

2. The dynamics of cloud impact: infinite thickness and uniform rotation

We first consider the energy balance of the interaction of an HVC with a gas disk. MacLow and Klessen (2004) showed that for interstellar gas clouds in general, support against gravitational collapse and maintenance of the observed internal velocity field depend on continued driving of the internal turbulence. The ratio R between the dissipation rate for isothermal supersonic turbulent energy and that supplied by the shock front caused when the HVC impinges on the interstellar medium (ISM) of the Galactic disk is:

$$R = \frac{\frac{\rho_{ISM} {V_{rms}^{ISM}}^{3}}{L_d}}{\frac{\rho_{HVC} V_{HVC}^{3}}{d}} \tag{1}$$

where ρ_{ISM} and ρ_{HVC} are the respective densities of the ISM and the HVC, V_{rms}^{ISM} is the characteristic turbulent velocity of the ISM, V_{HVC} is the approach velocity of the HVC, L_d is the driving scale, and $d \sim L_d$ is the characteristic scale of the shock front. Using values derived from observation we adopt: $\rho_{ISM} \sim 1 \mathrm{cm}^{-3}$, V_{rms}^{ISM} ranges from 0.7km s^{-1} for HI to 10 km s^{-1} for HII, $\rho_{HVC} \sim 10^{-4}$ cm^{-3}, and $V_{HVC} \sim$ 150 km s^{-1}. One must note that the directly observed value is the column density, and that there remains many uncertainties in the HVC distances. So one must take some assumptions to obtain the spatial HVC density. In this sense we follow Blitz et al. (1999) in taking distances of 1 Mpc, diameters of an HVC about 28 kpc, neutral hydrogen masses of $3.4 \times 10^{7} M_{\odot}$, total neutral gas masses of $4.7 \times 10^{7} M_{\odot}$, and total masses of $3.2 \times 10^{8} M_{\odot}$. Of course, a mean density so small might require some clumpiness for the cloud to remain neutral even in the metagalactic radiation field. however, the value obtained for the spatial density for HVCs is very similar to that obtained independently by Maller & Bullock (2004) for a low-density medium that surrounds Milky Way galaxy. Using these values we obtain a range in R between 10^{-3} and 3. For values of $R \leq 1$ the impact of the HVC will be sufficient to break the equilibrium of gas clouds, leading to gravitational collapse and in turn to possible star formation so that we can already see that in general terms the star forming process will tend to be accelerated by the impact of a large HVC on the gas disk.

We will now take a more quantitative look at the effect of the infall of a large HVC onto the plane of a galaxy following Chandrasekhar (1954). We will do this by examining the way the dynamical input affects the Jeans condition for the collapse of a gas cloud in the plane, introducing the force of the shock front induced by the HVC which leads to the (modified) Jeans condition. We first write down, in a simplified way, the dynamical equations. These include the equation of mass conservation, and that describing the generation of the gravitational field. To enable us to obtain analytically resolvable equations we make the highly simplifying assumptions that the Galactic disk is an extended homogeneous gaseous disk with an angular velocity $\vec{\Omega}$. Then the fluctuations in the velocity field $\vec{u}$, density $\delta\rho$, pressure δp, and gravitational potential δV are governed by the linearized equations:

$$\rho\frac{\partial\vec{u}}{\partial t} = 2\rho\vec{u}\times\vec{\Omega} - gr\vec{a}d\delta p + \rho gr\vec{a}d\delta V \pm (0, 0, \frac{\delta\rho V_{HVC}^2 10^{-4}}{3d}) \tag{2}$$

$$\frac{\partial\delta\rho}{\partial t} = -\rho div\vec{u} \tag{3}$$

$$\nabla^2\delta V = -4\pi G\delta\rho \tag{4}$$

Where we assumed that the HVC falls perpendicularly to the plane of the disk (in the z direction) and that $\rho_{HVC} \sim 10^{-4}\rho_{ISM}$. In the last term on the right hand side of eq. (2) a positive value would imply that during the interaction of the HVC with the disk the shock front destabilizes some fraction of the gas (although we have assumed uniform density for the purpose of the computation in practice there will be density variations, and the denser parts of the gas will clearly have the highest probability of being destabilized) favouring gravitational collapse, while a negative value would imply that after a relaxation time (characteristic of giant molecular clouds in a realistic ISM) those clouds which have not collapsed to form stars will incorporate the shock energy as internal turbulent energy,(the stability of these clouds is thereby increased), until the energy is dissipated and equilibrium is re-established.

This last term comes from an extension of Huang & Weigert (1982) who takes for the flux of momentum in the shock front the expresion $\rho v^2/d$, being v the r.m.s. velocity of gas.

In order to solve the system of equations we make some conventional approximations. If the changes in pressure and density are assumed to occur adiabatically, then $\delta p = c^2\delta\rho$, where c is the sound speed. We choose coordinate axes such that $\vec{\Omega}$ = (0,0,Ω), and we derive solutions corresponding to waves which propagate in the z direction. In this case $\partial/\partial z$ is the only non-vanishing component of the parameter gradient. The equations then take the form:

$$\frac{\partial u_x}{\partial t} - 2u_y\Omega) = 0 \tag{5}$$

$$\frac{\partial u_y}{\partial t} + 2u_x\Omega = 0 \tag{6}$$

$$\frac{\partial u_z}{\partial t} + \frac{c^2}{\rho}\frac{\partial\delta\rho}{\partial z} \mp \frac{10^{-4}V_{HVC}^2\delta\rho}{3d} - \frac{\partial\delta V}{\partial z} = 0 \tag{7}$$

$$\frac{\partial\delta\rho}{\partial t} + \rho\frac{\partial u_z}{\partial z} = 0 \tag{8}$$

$$\frac{\partial^2\delta V}{\partial z^2} + 4\pi G\delta\rho = 0 \tag{9}$$

For a solution representing the propagation of waves along the z axis we have $\partial/\partial t = i\omega$ and $\partial/\partial z = ik$ where ω denotes the frequency and k the wave number. Substituting in the differential equations we obtain a system of linear homogeneous equations for the amplitudes of the various parameters which can be written in matrix notation. The condition that this matrix equation has a non-trivial solution is that the determinant of the matrix of the coefficients must vanish. Expanding this determinant we find that it can be reduced to the form:

$$\omega^4 - 4\omega^2\Omega^2 + 4\Omega_3^2\Omega^2 = 0 \tag{10}$$

where $\Omega_3^2 = c^2k^2 - 4\pi G\rho \mp 10^{-4}V_{HVC}^2 k/3d$, $\Omega^2 = |\vec{\Omega}|^2$. From this we infer that waves can be propagated through the medium in two modes ω_1 and ω_2 which relates as $\omega_1\omega_2 = 2\Omega_3\Omega$.

3. The dynamics of cloud impact: the effect of uniform rotation for a disk of finite thickness

Here we will follow Goldreich & Lynden-Bell (1965a) in considering a uniformly rotating disk of scale height T, and that a region of this disk of horizontal scale k^{-1} is gravitationally unstable if energy is released when the region contracts slightly. Then the condition that energy be released in this way is equivalent to the condition that the region's self-gravitational energy be greater than the sum of its internal plus its rotational energies, to which we add the energy of the shock front induced by the infall of a giant HVC in the same way as in the previous section. So, the condition for stability will be:

$$\frac{4\pi G\rho}{k^2 + T^{-2}} = \frac{\Omega^2}{k^2} + c^2 \mp \frac{10^{-4}V_{HVC}^2}{3dk} \tag{11}$$

Taking observed values for the parameters: $d\sim 10pc$, $k\sim 2\pi/(0.1 - 100pc)$ and $T\sim 500pc$, we have $k^2\sim 10^{-3}$ while $T^{-2}\sim 10^{-6}$, so that equation (15) becomes:

$$4\pi G\rho = \Omega^2 + k^2c^2 \mp \frac{10^{-4}V_{HVC}^2 k}{3d} \tag{12}$$

And we can see that the term Ω^2 is of the same order as the others in equation (16) only if k is less than $2\pi/10pc$. So we obtain that for instabilities of size less than 10pc (the bulk of the stars observed in the disk arise from instabilities of $\sim$1pc to end as $1M_{odot}$) the uniform rotation does not affect the Jeans criterion even when we consider finite thickness for the disk.

4. The dynamics of cloud impact: shearing-box and infinite thickness

Here we model the stability of a uniform medium, of infinite extent in all directions, which is uniformly sheared in rotating axes. To do so, we again follow Goldreich & Lynden-Bell (1965b). The equation of motion in rotating axes is

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u}.\vec{\nabla})\vec{u} + 2\vec{\Omega}x\vec{u} - \Omega^2\vec{r} = \vec{\nabla}\psi - \frac{\vec{\nabla}p}{\rho} \pm \frac{\rho_{HVC}V_{HVC}^2}{\rho 3d}\vec{e} \tag{13}$$

where $\vec{u}$ is the fluid velocity, $\vec{\Omega} = (0, 0, \Omega)$ is the angular velocity of the axes. $\vec{r} = (x, y, 0)$ is the radius vector from the rotation axis, ψ is the gravitational potential, ρ the density of the fluid, p is the pressure of the fluid, and $\vec{e}$ is the unit vector in the direction of falling HVC. Assuming a polytropic fluid: $p = \kappa\rho^\gamma$, we have $\Psi = \psi + log\rho(-\kappa \pm V_{HVC}^2/d)$ with the only assumption that $\nabla\rho \sim \alpha^{-1}\rho_{HVC}$ with α some constant. We transform to sheared axes, co-moving with the unperturbed flow as its usual: $x' = x$, $y' = y - 2Axt$, $z' = z$ and $t' = t$ with A being the first Oort constant. Linearizing and including the perturbed Poisson equation (see Goldreich and Lynden-Bell) we have

$$\Psi_1 = \left(\frac{4\pi G\rho_0}{k^2(1+\tau^2)} - c^2 \pm \frac{\alpha V_{HVC}^2}{3dk} \right) \theta_1 \tag{14}$$

where $\tau = 2At' - k_x/k_y$, $\theta_1 = \rho_1/\rho_0$, and the sound velocity $c^2 = \kappa\gamma\rho_0^{\gamma-1}$. Then, the equation for axially-symmetrical "ring" modes with $k_y = 0$ may be obtained by taking a limiting procedure for $\tau{\sim}0$

$$\frac{d^2\theta_1}{d\tau^2} + \left(\frac{B\Omega}{A^2} - \frac{\pi G\rho_0}{A^2} + \frac{k^2(c^2 \mp \frac{\alpha V_{HVC}^2}{3dk})}{4A^2} \right) \theta_1 = 0 \tag{15}$$

where B is the second Oort constant. This equation is a simple harmonic so the "ring" waves are stable or unstable according to whether

$$4B\Omega - 4\pi G\rho_0 + k^2c^2 \mp \frac{\alpha k V_{HVC}^2}{3d} \tag{16}$$

is greater than 0, or less than or equal to 0 respectively. In this case we can see that the differential rotation does have a significant effect (the term $4B\Omega$ can be of the same order of magnitude as the gravitational term and also the pressure term). However, if the gradient of gas density in the shock front takes values of the same order than those of the ISM gas density, and as the ISM gas density is $\sim 10^4$ times the HVC gas density , we have $\alpha{\sim}10^{-4}$, and so we obtain similar values for the HVC effect to those for the other two effects. This implies that in all the cases studied here, the effect caused by the infall of a giant HVC over the disk is to trigger the gravitational collapse by destabilizing the GMC gas clouds, and favouring the formation of stars with masses near $1M_\odot$ as is observed (see e.g. Scalo 1986).

5. Implications for cloud collapse

We can see that if, in the model described in section 2, Ω_3 is imaginary this means that either ω_1 or ω_2 must be imaginary, so that in all cases there will be a mode of wave propagation which becomes unstable when Ω_3 becomes imaginary. We can write down the condition for Ω_3 to become imaginary as:

$$c^2k^2 \mp \frac{10^{-4}V_{HVC}^2 k}{3d} \leq 4\pi G\rho \tag{17}$$

This is clearly just the Jeans condition, modified by a term implied by the collision of the HVC with the galactic gas disk. In the models in sections 2 and 3, i.e for infinite thickness and uniform rotation and for finite thickness and uniform rotation, to first order (i.e. for linearized equations) the condition for gravitational instability is not affected significantly by the Coriolis force, but is clearly affected by collision with a large HVC. We now select a set of characteristic values for the parameters in the equation: $c{\sim}200ms^{-1}$, $k{\sim}2\pi/1$ (length in pc) for an ISM mass of $\sim 1M_{\odot}$, choosing this as a typical stellar mass, $V_{HVC}{\sim}150kms^{-1}$, $\rho{\sim}1M_{\odot}pc^{-3}$, and $d{\sim}10pc$ (which is taken directly from a theoretical model of shock fronts in the ISM by Huang and Weigert 1982). With these values we find that

$$c^2k^2 \sim \frac{10^{-4}V_{HVC}^2 k}{3d} \tag{18}$$

In the case treated in section 4 of infinite thickness and a shearing box approximating differential rotation, we clearly find that the rotation does affect the Jeans criterion for gravitational instability in the sense of favoring the cloud collapse since B, the second Oort constant, is negative. And also in this case the shock front produced by the falling HVC is of the same order as the others. This implies that in an ISM in which all or part of the gas is in a state close to gravitational collapse equilibrium the impact of an HVC will often be sufficient to squeeze the gas clouds into star-forming collapse. Clearly the values chosen here have been specific, but the result gives a rather general guide to a situation which may well occur widely in disk galaxies moving through an IGM in which there are clouds of gas with the densities of order 10^{-4} cm^{-3} as assumed here.

6. Conclusions

This simple but direct approximate treatment of the dynamical input to a rotating gas disk due to the infall of a high velocity cloud with characteristic physical properties derived from observations has shown us how the Jeans criterion for stability against collapse is modified by the dynamical effect of the infalling cloud. The modification is expressed in a single term added to the left hand side of the stability condition. Using typical values for the parameters we show that for the three cases this term is similar in amplitude to the original term found in the simplest standard Jeans case, but only if one introduce the differential rotation through the shearing-box approximation one find that also the rotating term is equaly important. This result shows that in a variety of circumstances the impact of an HVC with densities small compared to that of the disk gas on the will be to trigger those clouds which were close to equilibrium into a state of collapse, and hence by inference will tend to trigger star formation in any galactic disk where the previous conditions prevailing are those close to equilibrium against gravitational collapse. This strongly suggests that HVC's should be effective in triggering star formation under these circumstances, a conclusion which may have rather wide implications for galaxy evolution.

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