A Large Scale Energy Source For Feeding ISM Turbulence in Spiral Galaxies

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Abstract. One of the important consequences of a newly discovered secular dynamical evolution process of spiral galaxies (Zhang 1996, 1998, 1999) is that the orbiting disk matter receives energy injection each time it crosses the spiral density wave crest. This energy injection has been shown to be able to quantitatively explain the observed age-velocity-dispersion relation of the solar neighborhood stars. We demonstrate in this paper that similar energy injection into the interstellar medium could serve as the large-scale energy source to continuously power the observed interstellar turbulence and to offset its downward cascade tendency.

Keywords: turbulence, ISM, spiral density wave shock

1. Introduction

It has been several decades since it was first noticed that Galactic molecular clouds and complexes appear to be in a well-organized hierarchy, with their sizes and velocity dispersions following a power-law correlation, for cloud sizes ranging from 1 kpc which is the size of the Giant Molecular Cloud (GMC) and HI Complexes, down to 0.1 parsec which is the size of the cores of low mass star-forming regions. This observed hierarchy of cloud sizes and velocity dispersions has been speculated to be produced by a hierarchy of turbulent energy cascade (Larson 1981).

Due to the natural tendency of turbulence to cascade downward from large to small scales, its maintenance requires continuous kinetic energy injection at larger scales. Many candidate mechanisms for energy injection into the interstellar medium (ISM) have been envisioned over the past few decades. It is generally agreed that the relevant mechanism has to at least provide some means of energy injection from the largest scales, i.e. ~ 1 kpc. Small-scale energy injection mechanisms alone generally have difficulty in producing the observed large-scale correlation; the resultant hierarchy also has velocity dispersions largest on the smallest scales and smallest on the largest scales, contrary to the observed trend.

The most obvious reservoir of turbulent energy on the largest-scale is of course the galactic rotation. One problem with the past-proposed
means of tapping into this energy reserve is that galactic shear when coupled to the cloud-complex length scale causes these complexes to rotate with a much higher velocity than observed. Furthermore, detailed numerical simulations show that it is in fact rather difficult to couple the galactic rotation energy into internal motion energy of the cloud (Das and Jog 1995).

We introduce below a mechanism which can effectively tap into the energy reserve of galactic rotation without causing significant vortical motion of the clouds. The mechanism operates through the mediation of the spiral density wave, and is a byproduct of the energy and angular momentum exchange process between the density wave and the disk matter at the quasi-steady state of the wave mode.

2. Energy Injection into the Star-Gas Two-Fluid through the Spiral Collisionless Shock

For an open spiral wave mode, the potential and density spiral patterns are phase-shifted from each other in azimuth. Inside corotation, the potential spiral lags the density spiral and vice versa outside corotation (Zhang 1996). The existence of the phase shift indicates that there is a secular torque by the spiral wave on the disk matter, and, at the quasi-steady state of the wave mode, a secular energy and angular momentum transfer between the disk matter and the density wave, which is mediated by a local gravitational instability at the spiral arms (Zhang 1996).

Associated with the energy and angular momentum transfer between the disk matter and the wave there is heating of the disk matter, due to the fact that the wave pattern speed $\Omega_p$ is in general not equal to the angular speed of the matter $\Omega$. Specifically, we have that the rates of loss of orbital energy and angular momentum of the basic state matter per unit area are related through

$$\frac{dE_{\text{basic state}}}{dt} = \Omega \frac{dL_{\text{basic state}}}{dt},$$  \hspace{1cm} (1)

and the rates of gain of energy and angular momentum by the wave are related through

$$\frac{dE_{\text{wave}}}{dt} = \Omega_p \frac{dL_{\text{wave}}}{dt}. \hspace{1cm} (2)$$

Since $dL_{\text{basic state}}/dt$ is equal in magnitude to $dL_{\text{wave}}/dt$, it follows that the rate of random energy gain per unit area of the disk matter is related to the angular momentum exchange rate per unit area through

$$\frac{d\Delta E}{dt} \equiv \frac{d(E_{\text{basic state}} - E_{\text{wave}})}{dt} \equiv (\Omega - \Omega_p) \frac{dL_{\text{wave}}}{dt}, \hspace{1cm} (3)$$
where $L_{\text{wave}}$ is the angular momentum density of the wave. Note that this expression is true (and has a positive sign) both inside and outside corotation, since both $\Omega - \Omega_p$ and $dL_{\text{wave}}/dt$ change sign across corotation.

The above expression can be further written in terms of the spiral parameters by (Zhang 1998)

$$\frac{d\Delta E}{dt} = \frac{1}{2} (\Omega - \Omega_p) F^2 v_c^2 \tan i \sin(m\phi_0) \Sigma_0,$$

where $i$ is the pitch angle of the spiral, $m$ is the number of spiral arms, $\phi_0$ the potential and density phase shift, $F$ the fractional amplitude of the spiral, $v_c$ the circular speed of the galaxy, and $\Sigma_0$ the surface density of the disk. Equation (4) gives the rate of random energy increase of matter per unit area, valid for both the stellar and the gaseous components. For the former, it has been previously shown that this process could quantitatively account for the age-velocity dispersion relation of the solar neighborhood stars (Zhang 1999).

### 3. The Rate of Energy Injection and Rate of Energy Cascade

For the case of the ISM, we check out below that the above rate of energy injection (with the injected energy being the orbital energy converted into random energy by the spiral density wave) is comparable to the rate of downward turbulent energy cascade.

The average rate of energy injection per unit mass into the orbiting disk matter, using the fitted value of the stellar velocity diffusion coefficient $D^{3d}$ of $D^{3d} = 6 \times 10^{-7}$ (km/sec)$^2$ yr$^{-1}$ (Wielen 1977; Zhang 1999), is

$$\frac{d\Delta E}{dt} = \frac{1}{2} \frac{d\Delta v^2}{dt} = \frac{1}{2} D^{3d} = 3 \times 10^{-7} (\text{km/sec})^2 \text{yr}^{-1}. \quad (5)$$

On the other hand, the rate of energy cascade is, using the eddy turnover formula of von Weizsacker (1951) and using the standard values of the Galactic molecular cloud velocity dispersions of 10 km/sec and complex size scale 1 kpc

$$\frac{\Delta v^3}{L} = \frac{(10 \text{km/sec})^3}{1000 \text{pc}} = 8.7 \times 10^{-7} (\text{km/sec})^2 \text{yr}^{-1}. \quad (6)$$

The two rates are quite comparable, taking into account of the fact that the average energy injection rate calculated above is an underestimate.
of the instantaneous energy injection rate during the crossing of the \(\sim 1\) kpc width spiral arm shock, since this average is taken over the time period of the entire orbital cycle, which included the long inter-arm migration period during which there is no energy injection from the spiral shock.

The analyses of the data for the Carina molecular complex region (Zhang et al. 2001) showed that the observed tight size-line-width correlation for this region could not have been due to the bipolar outflow or the energy injection from stellar radiation, since the correlation is the same no matter a given cloud is near or away from the outflow, near or away from the young stars. There is also no known supernovae or superbubble in the surroundings of this region to serve as a possible energy injection source (Kornreich & Scalo 2000). Evidence suggests that the spiral density wave associated with the Carina arm was responsible for both a significant part of the cloud-heating of this region and for producing the observed size-line-width correlation which holds for this region of over 150 parsec in extent (Zhang et al. 2001).

The spiral density wave mechanism is capable of injecting energy to the disk matter on all scales, since it is operated through the gravitational potential on the disk matter, which eliminated the need of a direct coupling of energy from the size scale of 1 kpc to a few scales downward.

One interesting question would be the turbulent motion for the gas in the flocculent galaxies. Many flocculent galaxies are found to have more coherent underlying spiral structures in near infrared imaging (Thornley 1997). Even for those that do not possess grand design spirals, as long as there is significant evolution of galaxy morphology during which gravitational energy is constantly being converted into the random motion energy of the particles, the turbulence is still being continuously powered.

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