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Probing ISM Models with Hα Observations

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Abstract: I review the capabilities of Hα observations to constrain some aspects of the current models of the interstellar medium. In particular, it is shown that turbulence is a necessary ingredient of any viable model, since most of the energy produced by supernova explosions and ionising radiation is stored in kinetic form in the ISM. Various forms of turbulent energy dissipation, including cloud collisions, are analysed. Two additional aspects, concerning the existence of galactic fountains and their relation with high-velocity Clouds, and the extended ionised layer of spiral galaxies are discussed; some crucial experiments are suggested.

Keywords: interstellar medium — turbulence

1 Relevance of Hα Observations for the ISM

In spite of the impressive observational and theoretical advances that have occurred in the last decade, there are still a number of important issues concerning the structure and evolution of the Galactic interstellar medium (ISM) which require more study. Among these, three particularly relevant issues are discussed below. First, one would like to know to what extent the energy budget of the ISM is regulated by turbulence. Energy in this form is certainly supplied to the gas by the concurrent action of supernova explosions, winds from massive stars and HII regions. However, it is a difficult problem to ascertain the relative powers of these sources and the total amount of energy stored in different forms (i.e. thermal, radiative, magnetic and cosmic ray energy). Next, we understand that the disk of the Milky Way is not a closed system but is connected to the Galactic halo by different forms of energy transfer involving mass entrainment (particularly hot gas but also cold gas and dust) and photons leaking from the production regions. It is therefore important, both for energetic and evolutionary (chemical and dynamical) considerations, to assess the relevance of these disk/halo interactions, which are often referred to in brief as the Galactic Fountain. Finally, after more than 10 years since its firm discovery, the mystery of the existence of a vertically extended, ionised gas distribution, the so-called 'Reynolds layer' has not yet been dispelled. The aim of this work is to show how Hα observations can help us in making progress in each of these areas.

2 Turbulent Models of the ISM

Massive stars are probably the most important energy sources for the ISM. They inject power in both radiative (with ionising photons creating HII regions) and mechanical (supernova explosions) forms. The rate of *kinetic* energy density deposited via photoionisation is

$$\begin{aligned} W_u^{(k)} &= \alpha^{(2)} \langle n_e^2 \rangle \bar{E}_2 \\ &\sim 1 \cdot 9 \times 10^{-25} \left(\frac{\langle n_e^2 \rangle}{0 \cdot 1 \ \mathrm{cm}^{-6}} \right) \\ &\quad \mathrm{erg\ cm^{-3}\ s^{-1}}\,; \end{aligned} \tag{1}$$

the analogous quantity for a supernova explosion is

$$\begin{aligned} W_s^{(k)} &\sim 2 \cdot 2 \times 10^{-25} \left(\frac{\gamma}{0 \cdot 04 \ \mathrm{yr}^{-1}} \right) \\ &\quad \times \left(\frac{V_G}{78 \ \mathrm{kpc}^3} \right)^{-1} \mathrm{erg\ cm^{-3}\ s^{-1}}\,, \end{aligned} \tag{2}$$

where γ is the total (both Type I and II) supernova rate and V_G is the volume of the Galaxy (McKee 1990; Ricotti, Ferrara & Miniati 1997). Assuming efficiencies of kinetic energy conversion into the ISM of $\eta_u \sim 1\%$ and $\eta_s \sim 3\%$ (Spitzer 1978) for radiative and mechanical input, respectively, we find the total rate per unit volume at which energy available for motions in the ISM is produced: $W_i^{(k)} = \eta_u W_u^{(k)} + \eta_s W_s^{(k)} \sim 8 \times 10^{-27}$ erg cm^{-3} s^{-1}. Kinetic energy is mostly dissipated by cloud collisions at a rate

$$\begin{aligned} W_c^{(k)} &\sim 2 \cdot 2 \times 10^{-27} n \left(\frac{v_r}{14 \ \mathrm{km\ s}^{-1}} \right) \\ &\quad \times \left(\frac{t_i}{1 \cdot 1 \times 10^7 \ \mathrm{yr}} \right)^{-1} \mathrm{erg\ cm^{-3} s^{-1}} \\ &\sim 0 \cdot 25 W_i^{(k)}\,, \end{aligned} \tag{3}$$

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where n, v_r and t_i are the typical cloud density, relative velocity and the mean time interval between collisions, respectively. Thus there is clearly enough energy production to support the observed motions in the ISM.

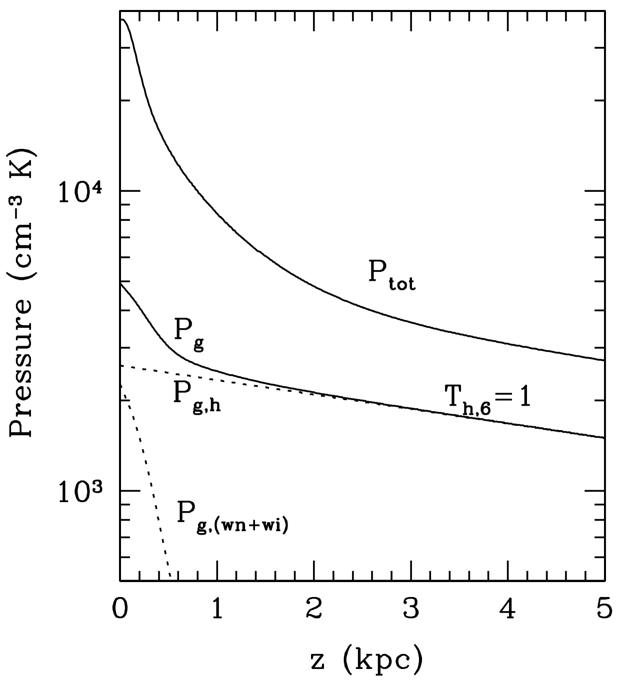

Figure 1—Thermal pressure contributions $P_{g,i}$ to the total pressure P_{tot} (determined from hydrostatic equilibrium) from the known gaseous phases of the ISM, where i = wn, wi, h indicate warm neutral, warm ionised, hot components, respectively. The difference $P_{tot} - P_g$ shows the importance of non-thermal (turbulent, magnetic, cosmic ray) forms of energy density.

These bulk motions have a strong impact on the structure of the Galactic ISM. For example, they are shown to largely regulate and reproduce the vertical distribution of the HI in the gravitational potential of the Galaxy (Lockman & Gehman 1991), once the effect of radiation pressure on dust grains embedded in clouds (the so-called 'photolevitation', Ferrara 1993) is properly taken into account. In addition, turbulence may be the most important form of energy storage in the ISM, as can be appreciated from Figure 1: the thermal pressure contributed by all known gaseous ISM phases, P_g, appears to be at most 13% of the total pressure, P_{tot}, as derived by imposing gas hydrostatic equilibrium in the Galactic gravitational field. Such a large ratio of the turbulent to thermal pressure implies a large porosity factor, Q, of the hot gas. McKee (1990) estimated that $Q \sim 1{\cdot}1(P_{turb}/P_{tot})^{\frac{4}{3}}$, implying $Q = 0{\cdot}92$ from the above estimates if the nonthermal energy is predominantly in turbulent form; this corresponds to a hot gas filling factor $f \sim 0{\cdot}6$.

Given these arguments it seems necessary to revise the current ISM models to include turbulence. A first attempt in this direction has been carried out by Norman & Ferrara (1996). The authors calculated the detailed grand source function (shown in Figure 2) for the conventional sources of turbulence from supernovae, superbubbles, stellar winds and HII regions. As seen from Figure 2, superbubbles are the main contributors to interstellar turbulence. In addition, from the study of the general properties of the turbulent spectrum, using an approach based on a spectral transfer equation derived from the hydrodynamic Kovasznay approximation, they conclude that the turbulent pressure calculated from the grand source function is $P_{turb} \sim 10$–$100P_g$. Also, given the scale-dependent energy dissipation from a turbulent cascade, the multi-phase medium concept has to be generalised to a more natural continuum description where density and temperature are functions of scale.

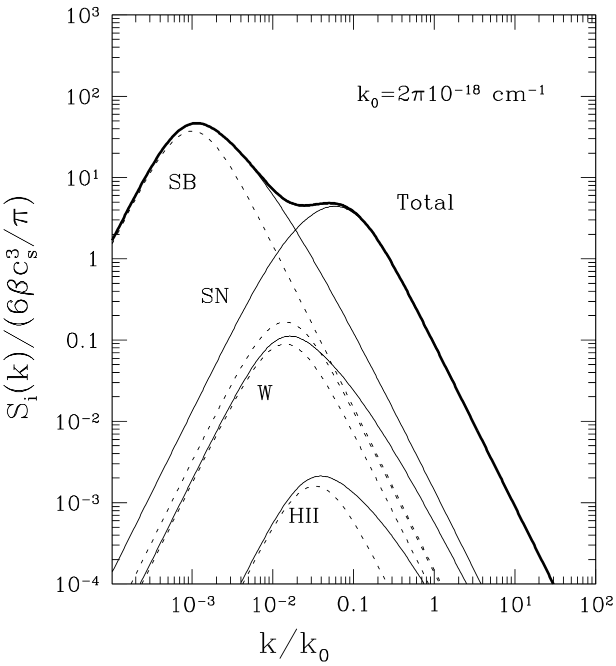

Figure 2—Normalised turbulent source functions $S_i(k)$ for supernovae, superbubbles, winds and HII regions. Solid lines show the sum of primary and secondary shock contributions for each source; dashed lines show secondary shocks only (see Norman & Ferrara 1996). The thick line is the total grand source function.

As recalled above, cloud collisions represent the most efficient dissipation mechanism of large-scale turbulence. The simple estimate for $W_c^{(k)}$ given above assumes that *all* the kinetic energy of the clouds is radiated away by the post-shock gas, i.e. an inelastic collision. This hypothesis is correct only in a restricted region of the collision parameters (velocity and mass ratio of the colliding clouds, magnetic field strength, gas metallicity). Ricotti et al. 1997 have studied the dependence of the elasticity (defined as the ratio of the final to the initial kinetic energy of the clouds) on such parameters (recently extended to

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include pre-interaction with the intercloud medium by Miniati et al. 1997). They find that (i) the collision elasticity is a maximum for a cloud relative velocity $v_r \simeq 30$ km s^{-1}; and (ii) the elasticity is $\propto ZL_c^2$, where Z is the metallicity and L_c is the cloud size: the larger ZL_c^2, the more dissipative (inelastic) the collision will be. During the collision the warm post-shock gas will radiate a substantial fraction of its internal energy in the Hα line depending on v_r and L_c. Figure 3 shows the Hα luminosity for a collision occurring ~1 kpc away from us for different values of v_r and L_c. Thus Hα observations can be used in principle as a powerful indicator of large-scale turbulent motion dissipation.

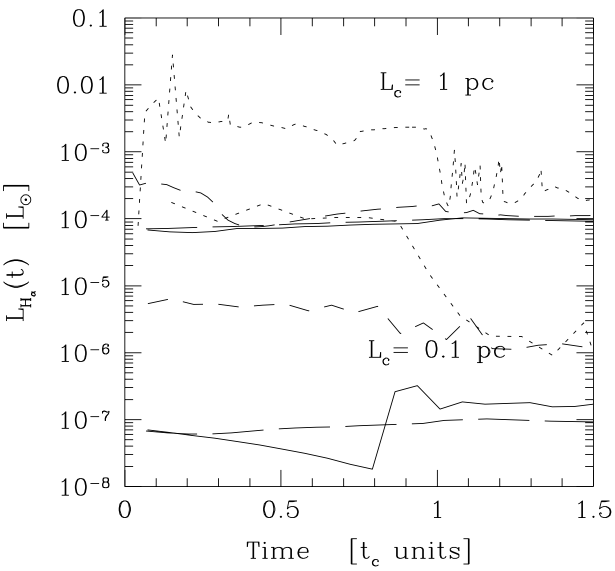

Figure 3—Hα luminosity evolution from cloud collisions at a distance of 1 kpc as a function of time in units of collision time ($t_c = L_c/v_r$). The upper (lower) group of lines refers to a cloud size $L_c = 1$ pc ($L_c = 0{\cdot}1$ pc) for different values of the relative velocity of the collision: $v_r = 6$ km s^{-1} (solid), $v_r = 16$ km s^{-1} (long-dashed), $v_r = 31$ km s^{-1} (short-dashed) and $v_r = 63$ km s^{-1} (dotted).

3 Does a Galactic Fountain exist?

One of the major predictions and elements in favour of the Galactic Fountain (GF) model (Shapiro & Field 1976; subsequently detailed by Bregman 1980) is the existence of the high velocity clouds (HVCs, recently reviewed by Wolfire et al. 1995) in the halo, as a by-product of the cooling of the hot fountain gas. Any constraint on the origin of HVCs would be highly valuable in terms of understanding the global disk/halo circulation. Ferrara & Field (1994) have investigated the ionisation and thermal structure of HVCs due to the extragalactic background radiation field and calculated the Hα emission from the partially ionised edge of a given cloud. Comparing the model results to the available Hα observations, the authors found that the observed Hα intensity is larger than the predicted one for all the different cases

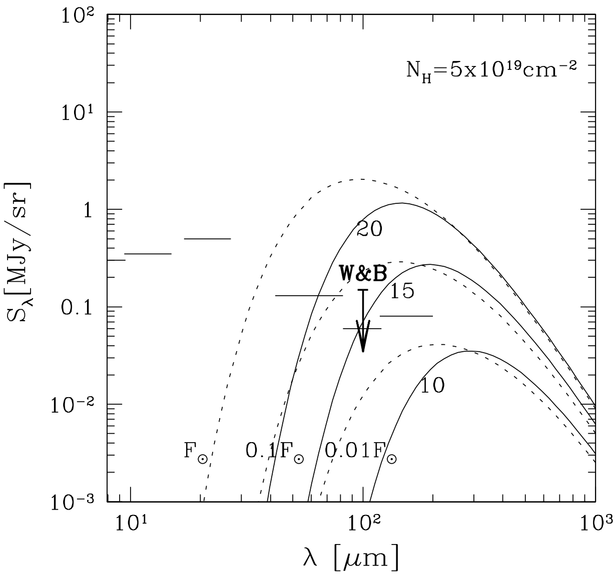

Figure 4—IR surface brightness from dust in HVCs with HI column density $N_{HI} = 5 \times 10^{19}$ cm^{-2}. Numbers refer to fixed grain temperatures (solid) or radiation flux intensity (dotted), where $F_\odot$ is the Galactic ISRF. Also shown are the Wakker & Boulanger (1986) limits and ISOPHOT sensitivity (see text).

considered. One possible cause of this discrepancy is that some of the observed emission is Hα light coming from the disk of the Galaxy and subsequently backscattered by dust in the clouds. Assessing the presence of dust in HVCs is a young research field and very little is known about this issue. However, there are theoretical bases on which to expect dust to be present. The efficiency of dust destruction in a shock (presumably the heating source for the fountain gas) is likely to be less than 10% (McKee 1989); the subsequent thermal sputtering in the hot gas might destroy some of the smallest grains: in a 10^6 K gas, the sputtering time is shorter than the gas cooling time only for grain sizes smaller than $0{\cdot}03$ μm. However, previous low-sensitivity searches using IRAS data have produced only upper limits (Wakker & Boulanger 1986) on HVCs, dust contents. In addition to the unlikely complete dust depletion, there are at least two other possibilities which might explain the non-detection: (i) HVCs are far above the Galactic plane ($\geq$10 kpc); and (ii) the dust is too cold to emit substantially in the IRAS bands. Since, at least for some of the clouds, the distance is bracketed around a much lower value for the distance, (i) is an unlikely explanation. It is quite possible, instead, that the dust is cold, due to the very diluted halo radiation field. The expected IR emission from a $N_{HI} = 5 \times 10^{19}$ cm^{-2} HVC, assuming either a given temperature of the grains or a galactic ISRF diluted by a given factor (1–100 times) is shown in Figure 4 together with ISOPHOT surface brightness limits (128 s of integration time, S/N = 10) in the various bands. Clearly, dust hotter than ~10 K and/or heated by an ISRF diluted by at

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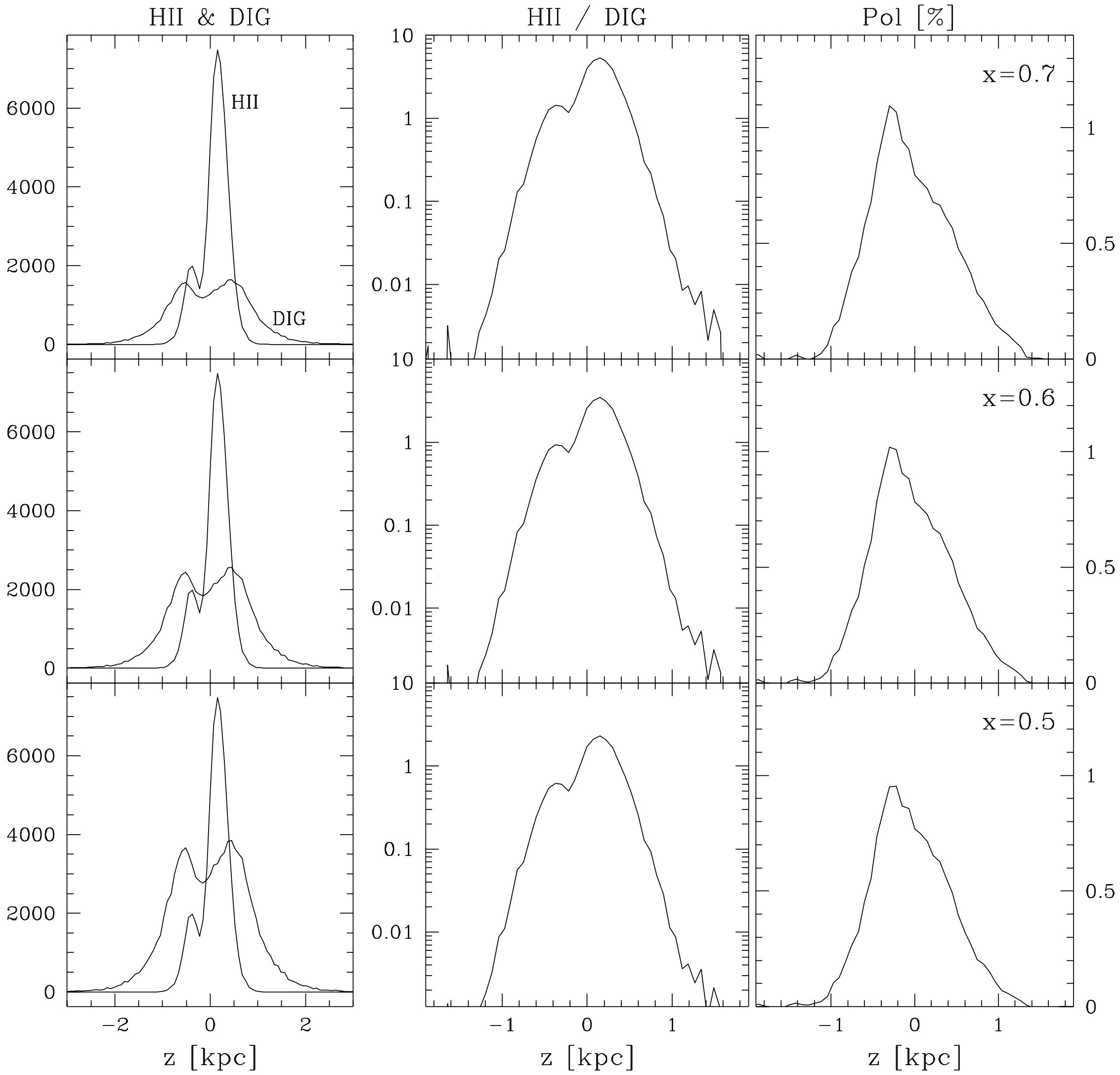

Figure 5—The z-axis cuts through the centre of NCG891 for (left column) the Hα luminosity profiles corresponding to contributions of HII regions and DIG component, (middle) the ratio of the two components, and (right) the profiles of the linear polarisation degree. Plots refer to the cases of $x = 0{\cdot}7$, $0{\cdot}6$, $0{\cdot}5$ (from top to bottom), where x is the ratio between Hα luminosity from H II regions to the total (DIG+H II regions) luminosity.

most 10 times could be detectable. Such a detection would bring strong support to the idea that HVCs are not of intergalactic origin and that they are very likely part of a global disk/halo circulation.

4 Hα from the Galactic DIG

The thick ($z \sim 1$ kpc) *Reynolds layer* of diffuse ionised gas (DIG) discovered in the Galaxy and in external ones poses some of the most challenging problems for our understanding of the large-scale structure of the Galactic ISM (Reynolds 1995). One of the best ways to study this component is represented by spectroscopic observations of emission lines like Hα, $[NII](\lambda 6583$ Å) and $[SII](\lambda$ 6716 Å). The different excitation conditions found in a given galaxy as a function of height above the plane pose a relevant question concerning the amount of light originating in the disk (where the most obvious ionisation sources are located) and light scattered back into the line of sight by dust. This aspect has been investigated recently by Ferrara et al. (1996), using Monte Carlo simulations to calculate the radiation transfer of Hα line emission, produced both by HII regions in the disk and in the DIG, through the dust layer of the galaxy NGC891.

The amount of light originating in the HII regions of the disk and scattered by EGD can be then compared with the emission produced by recombinations in the DIG. The cuts of photometric and polarimetric maps along the z-axis show that scattered light from HII regions is still 10% of that of the DIG at $z \sim 600$ pc (Figure 5), whereas the degree of linear polarisation is small ($< 1\%$). This could explain the observed behaviour of emission line ratios as a function of height (Ferrara et al. 1996).

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