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A NEW METHOD TO MEASURE AND MAP THE GAS SCALE HEIGHT OF DISK GALAXIES

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ABSTRACT

We propose a new method to measure and map the gas scale height of nearby disk galaxies. This method is applied successfully to the Australia Telescope Compact Array interferometric H I survey of the Large Magellanic Cloud (LMC); it could also be applied to a significant number of nearby disk galaxies, thanks to the next generation of interferometric facilities, such as the expanded Very Large Array and the Combined Array for Research in Millimeter-wave Astronomy. The method consists of computing the spectral correlation function (SCF) for a spectral line map of a face-on galaxy. The SCF quantifies the correlation between spectra at different map positions as a function of their separation and is sensitive to the properties of both the gas mass distribution and the gas velocity field. It is likely that the spatial correlation properties of the gas density and velocity fields in a galactic disk are sensitive to the value of the scale height of the gas disk. A scale-free turbulent cascade is unlikely to extend to scales much larger than the disk scale height since the disk dynamics on those larger scales should be dominated by two-dimensional motions. We find a clear feature in the SCF of the LMC H I disk, on the scale of ≈ 180 pc, which we identify as the disk scale height. We are also tentatively able to map variations of the scale height over the disk.

Subject headings: galaxies: ISM — galaxies: structure — Magellanic Clouds — turbulence

On-line material: color figures

1. INTRODUCTION

The gas scale height of galactic disks is an important quantity related to the process of star formation. It can be used to constrain the surface density of matter, the balance between star formation processes and gravity, and the interstellar medium pressure, which must be important for regulating star formation.

Optical images of edge-on galaxies show that the scale height of stellar disks are independent of position along their major axis (van der Kruit & Searle 1981, 1982; Kylafis & Bahcall 1987; Shaw & Gilmore 1990; Barnaby & Thronson 1992) or slowly increasing with radius (de Grijs & Peletier 1997). The constancy of the stellar scale height must be related to the radial and vertical distribution of the gas since molecular clouds are responsible for both the formation of stars and the dynamical heating of the stellar disk (Spitzer & Schwarzschild 1951).

The vertical distribution of neutral hydrogen in our Galaxy has been studied by many authors. It is found that the H I scale height h is approximately constant over a large range of Galactocentric radii (Dickey & Lockman 1990; Heiles 1991). It is commonly assumed that the H I gas is supported in the Galactic gravitational potential primarily by turbulence (Lockman & Gehman 1991), with contributions from magnetic and cosmic-ray pressure (Parker 1966; Spitzer 1990; Boulares & Cox 1990) and radiation (Franco et al. 1991; Ferrara 1993; Ferrara & Tolstoy 2000).

The constancy of the gas scale height in galactic disks is a common assumption in several models. However, it should not be taken for granted since direct measurements of the H I scale height in external galaxies are difficult and sparse and since the H I scale height has never been mapped in a face-on galaxy. A nearby edge-on galaxy where the H I distribution has been studied with very high linear resolution is NGC 891. Sancisi

& Allen (1979) found the H I disk of NGC 891 to be less than 1 kpc thick near the center, increasing outward up to 1–2 kpc. The H I disk flare is not confirmed in the later study by Swaters, Sancisi, & van der Hulst (1997), in which a significant H I halo component is instead identified, and it is pointed out that the inferred H I vertical density profile is dependent on the adopted kinematic model. The CO scale height for the same galaxy (≈ 220 pc) has also been estimated (Scoville et al. 1993).

In this Letter, we propose a new method to measure and map the H I scale height of face-on galaxies. The method is based on the application of the spectral correlation function (SCF) to H I interferometric surveys. The SCF (Rosolowsky et al. 1999; Padoan, Rosolowsky, & Goodman 2001) quantifies the correlation between spectra at different map positions as a function of their separation and is sensitive to the properties of both the gas mass distribution and the gas velocity field. The scale corresponding to the scale height of the H I disk should mark the transition from small-scale three-dimensional turbulence to two-dimensional large-scale motions on the disk since the ratio between radius and scale height of the cold gas in typical disk galaxies is very large (~ 100). This transition should appear as a feature in the SCF at a spatial lag approximately equal to the H I scale height. On smaller scales, the SCF should instead be a power law reflecting the self-similar nature of turbulence, as in molecular clouds (Padoan et al. 2001).

We have applied this method to the Australia Telescope Compact Array (ATCA) interferometric H I survey of the Large Magellanic Cloud (LMC) by Kim et al. (1998a, 1998b, 1999) combined with the single-dish survey done with the Parkes 21 cm Multibeam Receiver by L. Staveley-Smith et al. (2001, in preparation). Results of the combined survey are presented in Kim, Staveley-Smith, & Sault (2001). We find that the SCF is indeed a power law on small scales and has a characteristic

FIG. 1.—Velocity-integrated H I intensity in the LMC from the ATCA interferometric survey by Kim et al. (1998a, 1998b, 1999) combined with the single-dish survey done with the Parkes 21 cm Multibeam Receiver by L. Staveley-Smith et al. (2001, in preparation). The perimeter of each of the 25 regions used to compute the SCF is overplotted. [See the electronic edition of the Journal for a color version of this figure.]

feature at approximately 180 pc, where the power law is interrupted. We identify the scale of the clear “break” in the SCF as the H I scale height. We are also able to map significant variations of the scale height over the disk, between ≈ 140 and 240 pc.

In a recent work, Elmegreen, Kim, & Staveley-Smith (2001) have computed the power spectrum of H I intensity maps of the LMC from the same survey used in this work. They find that the power spectrum of intensity is steeper on small scales than on large ones. The transition occurs at approximately 80–100 pc and is interpreted as the line-of-sight thickness of the cold H I layer. The present Letter is qualitatively a confirmation of this earlier result, in the sense that both works show the possibility of using the statistical information from H I interferometric surveys to estimate the H I scale height of a face-on galaxy.

2. THE SCF METHOD

The SCF measures the correlation between spectra at different map positions as a function of their spatial separation and is sensitive to the properties of the gas mass distribution and the gas velocity field (Rosolowsky et al. 1999; Padoan et al. 2001). Let $T(\mathbf{r}, v)$ be the antenna temperature as a function of the velocity channel v at map position $\mathbf{r}$. The SCF for spectra with spatial separation $\Delta\mathbf{r}$ is

$$S_0(\Delta\mathbf{r}) = \left\langle \frac{S_0(\mathbf{r}, \Delta\mathbf{r})}{S_{0,N}(\mathbf{r})} \right\rangle, \quad (1)$$

where the average is done over all map positions $\mathbf{r}$. $S_0(\mathbf{r}, \Delta\mathbf{r})$

is the SCF uncorrected for the effects of noise,

$$S_0(\mathbf{r}, \Delta\mathbf{r}) = \left\langle 1 - \sqrt{\frac{\sum_v [T(\mathbf{r}, v) - T(\mathbf{r} + \Delta\mathbf{r}, v)]^2}{\sum_v T(\mathbf{r}, v)^2 + \sum_v T(\mathbf{r} + \Delta\mathbf{r}, v)^2}} \right\rangle_{\Delta\mathbf{r}}, \quad (2)$$

where the average is limited to separation vectors $\Delta\mathbf{r}$ with $|\Delta\mathbf{r}| = \Delta r$, and $S_{0,N}(\mathbf{r})$ is the SCF due entirely to noise,

$$S_{0,N}(\mathbf{r}) = 1 - \frac{1}{Q(\mathbf{r})}, \quad (3)$$

and $Q(\mathbf{r})$ is the “spectrum quality” (see discussion in Padoan et al. 2001). $Q(\mathbf{r})$ is computed as the ratio of the rms signal within a velocity window W to the rms noise N ,

$$Q(\mathbf{r}) = \frac{1}{N} \sqrt{\frac{\sum_v T(\mathbf{r}, v)^2 dv}{W}}, \quad (4)$$

where dv is the width of the velocity channels.

The SCF has been computed for both molecular cloud data and synthetic data obtained by solving the radiative transfer through the three-dimensional density and velocity fields of numerical simulations of supersonic MHD turbulence. The result is typically a power law that extends up to a separation Δr comparable to the map size, reflecting the self-similarity of supersonic turbulence (see Padoan et al. 2001 and references therein).

3. THE SCF AND THE SCALE HEIGHT OF THE LMC H I DISK

We have computed the SCF for several regions of the ATCA interferometric H I survey of the LMC by Kim et al. (1998a, 1998b, 1999) combined with the single-dish survey done with the Parkes 21 cm Multibeam Receiver by L. Staveley-Smith et al. (2001, in preparation). The original data have been rebinned to a resolution of $80''$ that is a linear resolution of 20 pc assuming a distance to the LMC of 50 kpc (Feast 1991). We therefore obtain a map made of 350×350 spectra (7×7 kpc), with 120 velocity channels. The velocity resolution is 1.65 km s^{-1} . Details about the ATCA survey can be found in Kim et al. (1998a, 1998b, 1999).

The finite size of a map with nonperiodic boundaries generates edge effects in correlation functions. In order to avoid this problem, we have computed the SCF for subsets of 50×50 spectra (1×1 kpc), excluding the data from the “edges” of the map. The spectra in each subset have been compared with all spectra within a larger area around that subset, including 150×150 spectra (3×3 kpc). In this way, the SCF for all the spectra in each subset can be computed up to a separation equal to the size of the subset (1 kpc), without any effects related to the finite size of the map.

Figure 1 shows the integrated H I intensity map of the LMC, divided into 7×7 subsets with 50×50 spectra each. The SCF has been computed only for the 5×5 central ones (delimited by the darker square) for which complete sets of 150×150 reference spectra are available. For lack of space, in Figure 2 we have plotted only the SCF computed inside the area marked with the rectangle in Figure 1.

Figure 2 shows that the SCF is a power law on small scales over almost an order-of-magnitude range in spectral separation Δr . The power-law slope of the SCF varies from -0.40 to -0.15 over the whole map. The power law is very clearly

FIG. 2.—SCF for the third and fourth columns of regions from Fig. 1. The regions are given coordinates (x, y) starting from $(0, 0)$ at the bottom left-hand corner of the 5×5 square in Fig. 1. [See the electronic edition of the *Journal* for a color version of this figure.]

interrupted at ≈ 180 pc, where the slope of the SCF generally decreases. In 22 of the 25 regions, the SCF breaks to a “shallower” slope on larger scales. It sometimes becomes steeper again on the scale of a few hundred parsecs, probably because of the effect of differential rotation, which grows with increasing spectral separation. In only three of the 25 cases, the SCF breaks from a power law to a “steeper” slope. This happens in the three regions around the location of 30 Doradus and south of it (the three regions covering the largest intensity feature on the bottom left of the map in Fig. 1).

We interpret the interruption of the power-law shape of the SCF as the outer scale of three-dimensional supersonic turbulence in the LMC disk. A scale-free cascade of three-dimensional turbulence is unlikely to extend to scales much larger than the disk scale height since two-dimensional flows should virtually dominate the dynamics on those larger scales. The power-law shape of the SCF for the H I data reflects the presence of self-similar turbulence, probably extending to much smaller scales than probed by the present survey (20 pc in our rebinned data). Below 20 pc, the turbulent cascade is well probed by the SCF of molecular emission-line maps (see Padoan et al. 2001).

Assuming that the SCF is indeed sensitive to the H I scale height h , we find that h varies in the range $130 \text{ pc} < h < 280 \text{ pc}$ over the surveyed area. The largest value is found in the region around 30 Doradus. The statistical error bars are smaller than the size of the symbols used in the plots in Figure 2, and variations of h are therefore significant. Figure 3 shows a contour

FIG. 3.—Contour map of the SCF scale height of the LMC disk. The values of the contour lines are in parsecs. The intensity map shows the same H I integrated intensity as in Fig. 1. [See the electronic edition of the *Journal* for a color version of this figure.]

map of h over the 5×5 regions where the SCF has been computed. The average value is $\langle h \rangle \approx 176$ pc. Kim et al. (1999) estimated the H I scale height using the average vertical velocity dispersion and the average surface density of both the H I and the stellar components of the LMC disk and adopting the disk model of Dopita & Ryder (1994). They found that $h \approx 180$ pc. This is almost identical to the value of $\langle h \rangle$ estimated with the SCF method, which is the main reason why we interpret the outer correlation scale of the SCF as the local value of the disk scale height. Nevertheless, we cannot rule out possible alternative interpretations of the SCF results, and the subject deserves further study.

One way to test our interpretation is by applying the SCF method to a complete three-dimensional model of a gaseous disk. The disk model should at least account for the turbulent density and velocity fields, the large-scale differential rotation, and the vertical density gradient in a self-consistent way. It should also be computed on a very large numerical mesh ($\approx 500^3$), in order to be suitable for the analysis presented in this work. Given the challenges presented by such a study, the computation of the SCF on a three-dimensional disk model will be the subject of future works.

Elmegreen et al. (2001) have recently computed the power spectrum of H I intensity maps of the LMC obtained with data from the same survey used in this work. They find a steeper power spectrum on small scales than on large ones. The transition occurs at approximately 80–100 pc and is interpreted as the line-of-sight thickness of the H I layer, based on the theoretical results of Lazarian & Pogosyan (2000).

In this work, we confirm the possibility of using the statistical information from H I interferometric surveys to estimate the H I scale height of a face-on galaxy. However, there is a fundamental difference between the present Letter and the work by Elmegreen et al. (2001), apart from the different method of data analysis adopted. Elmegreen et al. (2001) implicitly as-

sume that the three-dimensional power spectrum of the turbulent density field is described by a unique power law over all scales and that the change in slope of the two-dimensional power spectrum of integrated intensity is merely a projection effect. Here, instead, we argue that there must be a physical transition in the statistical properties of the flow on a scale close to the disk scale height, which the SCF is sensitive to.

4. CONCLUSIONS

We have proposed a new way to measure and map the scale height of the gas in face-on disk galaxies, based on the application of the SCF to H I interferometric surveys. We have shown that this method can be applied successfully to the LMC. It can be applied to a number of nearby galaxies, depending on the spatial and velocity resolutions of H I or molecular transition interferometric surveys. The Berkeley-Illinois-Maryland Association survey of nearby galaxies (BIMA SONG; Regan et al. 2001), for example, has an angular resolution of approximately 6" (using the D- and C-array configurations) and can achieve approximately 3" with the B-array configuration. At the distance of 4 Mpc, a 3" resolution corresponds to a linear resolution of ≈ 60 pc. There are six galaxies within the approximate distance range between 2 and 4.5 Mpc in the BIMA SONG list: IC 0342, NGC 2403, NGC 2976, NGC 3031, NGC 4736, and NGC 4826. They could, in principle, be studied with this method. Prob-

lems with the CO surveys may arise as a result of the low surface filling factor of CO relative to H I and, in the particular case of BIMA SONG, as a result of the relatively low velocity resolution (4.06 km s^{-1}). However, a velocity resolution of approximately 1.0 km s^{-1} could be easily achieved with BIMA in these galaxies (T. T. Helfer 2001, private communication).

For 21 cm H I observations, a 50 km baseline in a radio interferometer gives a resolution of 16 pc at 4 Mpc. At 3 mm, CO gives the same kind of resolution on a 0.7 km baseline. Therefore, the synthesized beams of the immediate descendants of existing centimeter and millimeter interferometers (e.g., the Expanded Very Large Array and the Combined Array for Research in Millimeter-wave Astronomy) should be able to map many galaxies with more-than-adequate resolution for the SCF to be used to measure, and map out, the galactic scale height.

The application of this method to a number of galaxies could provide new important measurements of the gas scale height and its variations inside individual disks and between different galaxies. Once the scale height is measured, it can also be used, together with the observed vertical velocity dispersion, to put new constraints on the distribution of dynamical mass in galactic disks.

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