HI power spectrum of the spiral galaxy NGC628

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ABSTRACT

We have measured the HI power spectrum of the nearly face-on spiral galaxy NGC628 (M74) using a visibility based estimator. The power spectrum is well fitted by a power law $P(U) = AU^\alpha$, with $\alpha = -1.6 \pm 0.2$ over the length scale 800 pc to 8 kpc. The slope is found to be independent of the width of the velocity channel. This value of the slope is a little more than one in excess of what has been seen at considerably smaller length scales in the Milky-Way, Small Magellanic Cloud (LMC), Large Magellanic Cloud (SMC) and the dwarf galaxy DDO210. We interpret this difference as indicating a transition from three dimensional turbulence at small scales to two dimensional turbulence in the plane of the galaxy’s disk at length scales larger than galaxy’s HI scale height. The slope measured here is similar to that found at large scales in the LMC. Our analysis also places an upper limit to the galaxy’s scale height at 800 pc.

Key words: physical data and process: turbulence-galaxy:disc-galaxies:ISM

1 INTRODUCTION

Evidence has been mounting in recent years that turbulence plays an important role in the physics of the ISM as well as in governing star formation. It is believed that turbulence is responsible for generating the hierarchy of structures present across a range of spatial scales in the ISM (e.g. Elmegreen & scale 2004a; Elmegreen & scale 2004b). In such models the ISM has a fractal structure and the power spectrum of density fluctuations is a power law, indicating that there is no preferred “cloud” size.

On the observational front, the power spectrum analysis of HI intensity fluctuations is an important technique to probe the structure of the neutral ISM in galaxies. The power spectrum analysis in our own Galaxy, Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC) finds the power spectrum of the HI intensity fluctuation to be a power law. Cosmic variance and Hubble flow distance of $\sim 10$ Mpc. On the other hand, Sharina et al. (1996) estimated a distance of 7.8 ± 0.9 Mpc from the brightest blue star in the galaxy. This distance estimate matches with an independent photometric distance estimate by Sohn & Davidge (1996). In a recent study Vinkó et al. (2004a) inferred the distance to be 6.7 ± 4.5 Mpc by applying the expanding photosphere method to the hyperbolic and Ho pass-bands are also power law, indicating that there is no characteristic mass or luminosity scale for OB associations and star complexes.

Recently Begum et al. (2006) presented a visibility based formalism for determining the power spectrum of HI intensity fluctuations in galaxies whose emission is extremely weak. This was applied to a dwarf galaxy, DDO210. Interestingly, the HI power spectrum of this extremely faint, largely quiescent galaxy was found to be a power law with the same slope as that observed in much brighter galaxies. In this paper the same formalism is used to measure the power spectrum of HI intensity fluctuation in the nearby spiral galaxy NGC628.

NGC628(M74) is a nearly face-on SA(s)c spiral galaxy with an inclination angle in the range $6^\circ$ to $13^\circ$ (Kamphuis & Briggs 1992). It has a very large HI disk extending out to more than 3 times the Holmberg diameter (Kamphuis & Briggs 1992). Elmegreen et al. (2006) have found a scale-free size and luminosity distribution of star forming regions in this galaxy, indicating turbulence to be functional here. The distance to this galaxy is uncertain with previous estimates ranging from 6.5 Mpc to 10 Mpc. Briggs et al. (1980) and Kamphuis & Briggs (1992) have used a Hubble flow distance of $\sim 10$ Mpc. On the other hand, Sharina et al. (1996) estimated a distance of 7.8 ± 0.9 Mpc from the brightest blue star in the galaxy. This distance estimate matches with an independent photometric distance estimate by Sohn & Davidge (1996). In a recent study Vinkó et al. (2004a) inferred the distance to be 6.7 ± 4.5 Mpc by applying the expanding photosphere method to the hyperbolic and Ho pass-bands are also power law, indicating that there is no characteristic mass or luminosity scale for OB associations and star complexes.

According to the visibility based formalism, the power spectrum of HI intensity fluctuation is given by $P(U) = AU^\alpha$, where $A$ is a constant and $U$ is the spatial frequency. The slope $\alpha$ is found to be independent of the width of the velocity channel. This value of the slope is a little more than one in excess of what has been seen at considerably smaller length scales in the Milky-Way, Large Magellanic Cloud (LMC), Large Magellanic Cloud (SMC) and the dwarf galaxy DDO210. We interpret this difference as indicating a transition from three dimensional turbulence at small scales to two dimensional turbulence in the plane of the galaxy’s disk at length scales larger than galaxy’s HI scale height. The slope measured here is similar to that found at large scales in the LMC. Our analysis also places an upper limit to the galaxy’s scale height at 800 pc.

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per novae SN2002ap. Throughout this paper we adopt the photometric distance of 8 Mpc for NGC628. At this distance 1" corresponds to 38.8 pc.

In this paper we present the power spectrum of HI intensity fluctuations of NGC628 derived using the visibility based formalism developed by Begum et al. (2006). Studies of external galaxies like NGC628 which has a very extended HI disk holds the potential of probing the ISM and its power spectrum at length scales much larger than has been possible in earlier studies (Oey 2002).

2 DATA AND ANALYSIS

We have used archival HI data of NGC628 from the Very Large Array (VLA). The observations had been carried out on 1st August and 14th November, 1993 respectively in the C and D configurations of the VLA, as a part of the AAO163 observing program. The multi-configuration data were downloaded from the VLA archive and reduced in the usual way using standard tasks in classic AIPS. For each VLA configuration, bad visibility points were edited out, after which the data were calibrated. The calibrated data for both configurations was combined using DBCON. The HI emission from NGC628 spans 64 central channels of the 256 channel spectral cube (with channel width 1.29 km s⁻¹). A continuum image was made using the average of all the line free channels. The continuum from the galaxy was subtracted from the data in the w plane using the AIPS task UVSUB. The resulting continuum subtracted data was used for the subsequent analysis. Figure 1 shows a total HI column density (Moment 0) map of NGC628 from an image made from this data. The HI disc of the galaxy is nearly face-on. The angular extent of the HI distribution in Figure 1 is roughly 11' × 15'. Using deep VLA D array mosaic observations, Kamphuis & Briggs (1992) had detected a ∼ 38' × 31' faint diffuse HI envelope around NGC628. This extended envelope is not detected in the current dataset; the emission that we do detect is instead restricted to the main HI disc of NGC 628. The results we discuss below are hence also relevant only to the gas in the main HI disc around NGC628.

Begum et al. (2006) contains a detailed discussion of the visibility based HI power spectrum estimator \( \hat{P}_{HI}(U) = \langle V_\nu(U) V_\nu^* (U + \Delta U) \rangle \). We present only a brief discussion here. Every visibility \( V_\nu(U) \) is correlated with all other visibilities \( V_\nu(U + \Delta U) \) within a disk \( |\Delta U| \leq D \). We shall discuss the considerations for deciding the value of \( D \) shortly. The correlations are averaged over different \( U \) directions assuming that the signal is isotropic. To increase the signal to noise ratio we further average the correlations in bins of \( U \) and over all frequency channels with HI emission. The expectation value of the estimator \( \hat{P}_{HI}(U) \) is real and it is the convolution of the HI power spectrum \( P_{HI}(U) \) and a function \( |W_\nu(U)|^2 \) which can be assumed to be sharply peaked around \( U = 0 \) with a width of order \( D \). At baselines \( U \gg D \) the function \( |W_\nu(U)|^2 \) can be well approximated by a Dirac delta function and the expectation value of \( \hat{P}_{HI}(U) \) gives an estimate of the HI power spectrum \( P_{HI}(U) \). The value of \( D^{-1} \) is of the order of the angular extent of the HI emission (Figure 1), and we use \( D = 0.4K\lambda \) for our analysis.

The 1 – σ error-bars for the estimated power spectrum is a sum, in quadrature, of contributions from two sources of uncertainty. At small \( U \) the uncertainty is dominated by the fact that we have a finite and limited number of independent estimates of the true power spectrum, while at large \( U \) it is dominated by the system noise in each visibility.

The HI emission spans 64 frequency channels each of width 1.29 km s⁻¹. To determine if the slope of the HI power spectrum changes with the width of the frequency channel, we have combined \( N \) successive channels to obtain a data set with 64/\( N \) channels of width \( N \times 1.29 \text{ km s}^{-1} \) each. We have determined the HI power spectrum for a range of \( N \) values.

3 RESULTS AND DISCUSSION

Figure 2A shows the real and imaginary parts of \( P_{HI}(U) \), which is the observed value of the estimator \( \hat{P}_{HI}(U) \) for the 64 channels which have HI emission. As expected from the theoretical considerations mentioned earlier, the imaginary part is well suppressed compared to the real part. To test for a possible contribution from residual continuum, we also show the real part of \( P_{HI}(U) \) using 64 line free channels. This is found to be much smaller than the signal. For the channels with HI emission the observed \( P_{HI}(U) \) may be directly interpreted as the HI power spectrum at \( U \) values that are considerably larger than \( D = 0.4K\lambda \). We find that a power law \( P_{HI}(U) = AU^\alpha \) with slope \( \alpha = -1.6 \pm 0.2 \) provides a good fit to the results over the \( U \) range 1.0 K\( \lambda \) to 10.0 K\( \lambda \) (Figure 2B) which corresponds to spatial scales of 800pc to 8kpc.

Both HI density fluctuations as well as spatial fluctua-

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1 NRAO Astrophysical Image Processing System, a commonly used software for radio data processing.
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On the contrary, we find a slope \(-1.6 \pm 0.2\) for NGC628. This is a little more than one in excess of the earlier values. However, when comparing these values it should be noted that the earlier works have all measured the HI power spectrum at much smaller length scales in the range 10 to 500 pc [MW (5 pc – 200 pc), SMC (4 pc – 30 pc), DDO210 (80 pc – 500 pc)] whereas the current measurement probes much larger length scales from 800 pc to 30 kpc. The typical HI scale heights within the Milky-Way (Lockman et al. 1984; Wouterloot et al. 1990) and external galaxies (e.g. Narayan & Jos 2002) are well within 1.5 kpc. This implies that on the largest length scales which we have probed, the turbulence is definitely confined to the plane of the galaxy’s disk and is therefore two dimensional. Elmegreen et al. (2001) have found that the HI power spectrum of LMC flattens at large length scales, which was interpreted as a transition from three dimensional to two dimensional turbulence. We conclude that the slope is different in our observations because it probes two dimensional turbulence, whereas the earlier observations were on length scales smaller than the scale height where we can expect three dimensional turbulence. To the best of our knowledge our results are the first observational determination of the HI power spectrum of an external spiral galaxy at such large length scales which are comparable to the radius of the galaxy’s disk.

Westpfahl et al. (1999) have performed a fractal analysis using the perimeter-area dimension of intensity contours in HI images of several galaxies in the M81 group. Of particular interest is the galaxy M81, a spiral galaxy for which the perimeter-area dimension was found to be \(\sim 1.5\) at a length scale \(\sim 10\) kpc. This observation is consistent with a power law power spectrum of slope \(-1.6 \pm 0.2\) provided the assumption that the local dimension has the same value as the perimeter-area dimension is valid.

It is difficult to probe the HI scale height of external face-on galaxies. Padoan et al. (2001) present a method to

| N | \(\Delta V\) (kms\(^{-1}\)) | \(\alpha\) | 1\(\sigma\) |
|---|---|---|---|
| 1 | 1.3 | -1.7 | \(\pm 0.2\) |
| 32 | 42.3 | -1.6 | \(\pm 0.2\) |
| 64 | 82.5 | -1.6 | \(\pm 0.2\) |

This table sunrises the result for different channel width.

Figure 2. A) Real and imaginary parts of the observed value of the HI power spectrum estimator \(\hat{P}_{\text{HI}}(U)\) for \(N = 64\) ie. all frequency channels with HI emission were collapsed into a single channel. The real part is also shown using 64 line-free channels collapsed into a single channel. B) Best fit power law to \(\hat{P}_{\text{HI}}(U)\). The channel width is varied \((N = 1, 32, 64; \text{top to bottom})\), 1\(\sigma\) error-bars are shown only for \(N = 64\).

See also Figure 3. As the thickest channel that we have used is considerably wider than the typical HI velocity dispersion of \(7 \pm 2\) km s\(^{-1}\) seen in spiral galaxies (Shostak & van der Kruit 1984), we conclude that the observed HI power spectrum of NGC628 is purely due to density fluctuations. Our finding is similar to that of Begum et al. (2006) who noticed no change of the slope with channel width for the dwarf galaxy DDO210. Further, Elmegreen et al. (2001) also reported a similar behavior for LMC.

Earlier studies of the Milky-Way, and also of the dwarf galaxies LMC, SMC and DDO210 (Crovisier & Dickey 1983; Green 1993; Stanimirovic et al. 1999; Deshpande et al. 2001; Elmegreen et al. 2001; Begum et al. 2006) have all found a power law HI power spectrum with slope \(-3\).
probe the scale height from a change in the slope of the Spectral Correlation Function (SCF) [Rosolowsky et al. (1999)], and applied it to HI data for the LMC to estimate the scale height to be $\sim 180$ pc. Elmegreen et al. (2001) suggested that one could use a change in the slope of the power spectrum of the density fluctuations to measure the scale height of face on gas disks. Applying this method to HI data for the LMC they measure scale height of 100 pc. To the best of our knowledge, prior to this work, there has been no observational constraint on the HI scale height of NGC628. Since the scale height is definitely less than 8 kpc and the power spectrum is found to have the same slope from 800 pc to 8 kpc, we conclude that the scale height must be less than 800 pc. Kregel et al. (2004) present HI images of a large sample of edge on intermediate to late type spirals; from their data the ratio of the HI disk height to the radius of the HI disk (at a column density of $1M_\odot pc^{-2}$) is $\sim 0.06 \pm 0.15$. From Fig. 1 the disk of NGC628 has a diameter of $\sim 28$ kpc at this column density. From the average thickness to radius ratio for edge on galaxies, one would expect NGC628 to have a scale height of $\sim 840$ pc, consistent with our result. Future observations of NGC628 with higher angular resolution should be able to put a tighter constraint or even determine the scale height.

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REFERENCES

Begum, A., Chengalur, J. N., & Bhardwaj, S. 2006, MNRAS, 372, L33
Briggs, F. H., Wolfe, A. M., Krumm, N., & Salpeter, E. E. 1980, ApJ, 238, 510
Crovisier, J., & Dickey, J. M. 1983, AAP, 122, 282
Deshpande, A. A., Dwarakanath, K. S., & Goss, W. M. 2000, ApJ, 543, 227
Elmegreen, B. G., Kim, S., & Staveley-Smith, L. 2001, ApJ, 548, 749
Elmegreen, B. G., & Scalo, J. 2004a, ARAA, 42, 211
Elmegreen, B. G., Elmegreen, D. M., Chandar, R., Whitmore, B., & Regan, M. 2006, APJ, 644, 879
Green, D. A. 1993, MNRAS, 262, 327
Kamphuis, J., & Briggs, F. 1992, AAP, 253, 335
Kregel M., van der Kruit P. C., de Blok W. J. G., 2004, MNRAS, 352, 768
Lazarian, A. 1995, AAP, 293, 507
Lazarian, A., & Pogosyan, D. 2000, APJ, 537, 720
Lockman, F. J., Hobbs, L. M., & Shull, J. M. 1984, BAAS, 16, 981
Narayan, C.A. & Jog, C.J. 2002, AAP, 390, 35
Oey, M. S. 2002, ASPC, 276, 295
Padoan, P., Kim, S., Goodman, A., & Staveley-Smith, L. 2001, ApJL, 555, L33
Rosolowsky, E. W., Goodman, A. A., Wilner, D. J., & Williams, J. P. 1999, APJ, 524, 887
Scalo, J., & Elmegreen, B. G. 2004b, ARAA, 42, 275
Sharina, M. E., Karachentsev, I. D., & Tikhonov, N. A. 1996, AAP, 119, 499
Shostak, G. S., & van der Kruit, P. C. 1984, AAP, 132, 20
Sohn, Y. & Davidge, T. J., 1996, AJ, 111, 2280
Stanimirovic, S., Staveley-Smith, L., Dickey, J. M., Sault, R. J., & Snowden, S. L. 1999, MNRAS, 302, 417
Vinkó, J., et al. 2004, AAP, 427, 453
Westpfahl, D. J., Coleman, P. H., Alexander, J., & Tongue, T. 1999, AJ, 117, 868
Wouterloot, J. G. A., Brand, J., Burton, W. B., & Kwee, K. K. 1990, A&A, 230, 21