Turbulence in the harassed galaxy NGC 4254

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Accepted 2010 April 4. Received 2010 March 12; in original form 2010 January 25

ABSTRACT

Galaxy harassment is an important mechanism for the morphological evolution of galaxies in clusters. The spiral galaxy NGC 4254 in the Virgo cluster is believed to be a harassed galaxy. We have analysed the power spectrum of H\textsc{i} emission fluctuations from NGC 4254 to investigate whether it carries any imprint of galaxy harassment. The power spectrum, as determined using the 16 central channels which contain most of the H\textsc{i} emission, is found to be well fitted by a power law $P(U) = AU^\alpha$ with $\alpha = -1.7 \pm 0.2$ at length-scales 1.7 to 8.4 kpc. This is similar to other normal spiral galaxies which have a slope of $\sim -1.5$ and is interpreted as arising from two-dimensional turbulence at length-scales larger than the galaxy’s scaleheight. NGC 4254 is hence yet another example of a spiral galaxy that exhibits scale-invariant density fluctuations out to length-scales comparable to the diameter of the H\textsc{i} disc. While a large variety of possible energy sources like protostellar winds, supernovae, shocks, etc. have been proposed to produce turbulence, it is still to be seen whether these are effective on length-scales comparable to that of the entire H\textsc{i} disc. On separately analysing the H\textsc{i} power spectrum in different parts of NGC 4254, we find that the outer parts have a different slope ($\alpha = -2.0 \pm 0.3$) compared to the central part of the galaxy ($\alpha = -1.5 \pm 0.2$). Such a change in slope is not seen in other, undisturbed galaxies. We suggest that, in addition to changing the overall morphology, galaxy harassment also affects the fine scale structure of the interstellar medium, causing the power spectrum to have a steeper slope in the outer parts.

Key words: turbulence – Galaxy: disc – galaxies: ISM.

1 INTRODUCTION

Galaxy harassment (frequent high-speed galaxy encounters; Moore, Katz & Lake 1996) is believed to be an important process in driving the morphological transformation of spiral galaxies to ellipticals inside clusters. Typically, the first encounters convert a normal spiral galaxy to a disturbed spiral with dramatic features drawn out from the dynamically cold gas. The spiral galaxy NGC 4254, located in the nearby Virgo cluster, is found to have a tail (Minchin et al. 2005) with neutral hydrogen (H\textsc{i}) mass $2.2 \times 10^8 M_\odot$ within a distance of 120 kpc from the galaxy. This gaseous tail, without any stellar counterpart, is believed to have been produced by an act of galaxy harassment (Haynes, Giovanelli & Kent 2007). Each act of harassment has the potential to induce a burst of star formation and to change the internal properties of the galaxy, including the properties of the interstellar medium (ISM). Here we study the effect of the harassment on the fine scale structure of the ISM. We use the power spectrum of H\textsc{i} intensity fluctuations to quantify the fine scale structure.

Power spectrum analysis of the H\textsc{i} 21-cm intensity fluctuation has been widely used to probe the ISM (Crovisier & Dickey 1983; Green 1993; Stutzki et al. 1998; Stanimirovic et al. 1999; Deshpande, Dwarakanath & Goss 2000; Elmegreen, Kim & Staveley-Smith 2001; Elmegreen & Scalo 2004; Scalo & Elmegreen 2004). These studies, mainly of our Galaxy and its satellites, find a power-law power spectrum $P(U) = AU^\alpha$ with index $\alpha$ in the range $2.5$ to $3.0$. This scale-invariant power spectrum is interpreted as arising from turbulence in the ISM. Recently Begum, Chengalur & Bhardwaj (2006) have presented a visibility-based formalism for determining the power spectrum of galaxies with extremely weak H\textsc{i} emission. This has been applied to a sample of dwarf and spiral galaxies (Dutta et al. 2008, 2009a,b). These studies indicate a dichotomy in $\alpha$ with values $\sim -1.5$ in some galaxies and $\sim -2.5$ in others. The two values $\sim -1.5$ and $\sim -2.5$ are interpreted as arising, respectively, from two-dimensional (2D) and three-dimensional (3D) turbulence. Some support for this...
Fig. 1 shows an integrated HI column density (Moment 0) map of NGC 4254 (contours) is overlayed with the optical image of the galaxy (density). The contours levels are 3.0, 5.0, 10.0, 20.0, 25.0, 35.0, 40.0, and 45.0 $\times$ $10^{20}$ atoms cm$^{-2}$.

interpretation has been provided by analysis of the fluctuation power spectrum for NGC 1058 where a transition from 2D to 3D turbulence is observed at an angular scale corresponding to the scaleheight of the galaxy’s disc.

NGC 4254 is a lopsided spiral galaxy [morphological type SA(s)c], with an inclination of $\sim$42$^\circ$ (Phookun, Vogel & Mundy 1993). The galaxy is located at a distance of 1 Mpc from the core of Virgo cluster and is believed to be falling into the cluster with a relative velocity of 1300 km s$^{-1}$ (Vollmer, Huchtmeier & van Driel 2005). The distance to this galaxy is estimated to be 16.7 Mpc (Mei et al. 2007); at this distance 1 arcsec corresponds to 81 pc.

2 DATA AND ANALYSIS

We have used archival H I data of NGC 4254 from the Very Large Array (VLA). The observations had been carried out on 1992 March 4 and 5 using the C configurations of the VLA (Phookun et al. 1993). The data were downloaded from the VLA archive and reduced in the usual way using standard tasks in classic AIPS. The HI emission from NGC 4254 spans over 30 channels, i.e. (18 to 47) from 1401.7 MHz (2253 km s$^{-1}$) to 1416.4 MHz (2562 km s$^{-1}$) of the 63 channel spectral cube. A frequency width of 48.8 kHz for each channel in the data cube corresponds to the velocity resolution of 10.32 km s$^{-1}$. The continuum from the galaxy was subtracted from the data in the $uv$ plane using the AIPS task UVSUB. The resulting continuum subtracted data were used for the subsequent analysis.

Fig. 1 shows an integrated H I column density (Moment 0) map of NGC 4254 made from this data. The angular extent of the HI distribution in Fig. 1 is measured to be 6.5 $\times$ 8.0 arcmin$^2$ at a column density of $10^{19}$ atoms cm$^{-2}$, which is comparable to its optical diameter (de Vaucouleurs et al. 1991).

Begum et al. (2006) and Dutta et al. (2009b) contains a detailed discussion of the visibility-based HI power spectrum estimator $\hat{P}_{HI}(U)$, hence we present only a brief discussion here. Here $U$ refers to a baseline, i.e. the antenna separation projected in the plane perpendicular to the direction of observation, measured in units of the observing wavelength $\lambda$. It is common practice to express the dimensionless quantity $U$ in units of kilowavelength ($k\lambda$). Every visibility $V_\nu(U)$ is correlated with all other visibilities $V_\nu(U + DU)$ within a disc $|DU| < (\pi\theta_0)^{-1}$, where $\theta_0$ is the angular extent of the galaxy. The correlations are averaged over different $U$ directions assuming that the signal is statistically isotropic in the plane of the galaxy’s image. To increase the signal-to-noise ratio we further average the correlation 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 $P_{HI}(U)$ with a window function $|\hat{W}_\nu(U)|^2$. The window function, which quantifies the effect of the large-scale HI distribution and the finite angular extent of the galaxy, is peaked around $U = 0$ and has a width of order $(\pi\theta_0)^{-2}$ beyond which $|\hat{W}_\nu(U)|^2 \sim 0$. Analytic considerations and simulations (Dutta et al. 2009b) show that beyond a baseline $U_{bin} = 3.5\theta_0^{-1}$ the convolution does not affect the shape of the HI power spectrum, and we may directly interpret the real part of the estimator $\hat{P}_{HI}(U)$ as the HI power spectrum $P_{HI}(U)$.

The estimator $\hat{P}_{HI}(U)$ also has a small imaginary component arising mainly from noise. The 1σ 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 sample variance which comes from the fact that we have a finite and limited number of independent estimates of the true power spectrum. At large $U$, it is dominated by the system noise in each visibility.

3 RESULTS AND DISCUSSION

Fig. 2 shows the real and imaginary parts of $\hat{P}_{HI}(U)$ evaluated using 16 channels from 27 to 42 which have relatively high HI emission. Here the estimator $\hat{P}_{HI}(U)$ was separately evaluated for each channel and then averaged over all 16 channels to increase the signal-to-noise ratio. As expected from the theoretical considerations (Begum

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1 NRAO Astrophysical Image Processing System, a commonly used software for radio data processing.
The power law $P_{HI}(U) = AU^{\alpha}$, with $\alpha = -1.7 \pm 0.2$ is found to give a good fit to the HI power spectrum for the $U$ range 2.0 to 10.0 k$\lambda$ (Table 1). The best-fitting power law and the 1$\sigma$ error bar on $\alpha$ were determined using $\chi^2$ minimization (Begum et al. 2006; Dutta et al. 2009a). We use $D = 16.7$ Mpc (distance to the galaxy) to convert a baseline $U$ to a length-scale $D/U$ in the plane of the galaxy’s image. The $U$ range 2.0 to 10.0 k$\lambda$ corresponds to the range of length-scales 8.4 to 1.7 kpc. Dutta et al. (2009b) have broadly classified the observed turbulence in their galaxy sample as 2D turbulence at the large scales in the plane of the galaxies disc and 3D turbulence at scales smaller than the scaleheight of the disc. They also show that the slope of the power spectrum changes from $\sim -1.5$ to $\sim -2.5$ as one goes from 2D to 3D turbulence. For the present case the largest length-scale (8.4 kpc) is definitely larger than the typical HI scaleheights within the Milky Way (Lockman, Hobbs & Shull 1984; Wouterloot et al. 1990) and in external spiral galaxies (e.g. Narayan & Jog 1990). It is thus quite reasonable to conclude that the slope $\alpha = -1.7 \pm 0.2$ is of 2D turbulence in the plane of the galaxy’s disc. The fact that we do not observe the transition to 3D turbulence, which is expected to occur at a baseline $U = D/\pi z_0$ (Dutta et al. 2009b), allows us to place an upper limit on the galaxy’s scaleheight $z_0 \leq 2.6$ kpc.

Our present observation is another confirmation (Dutta et al. 2008, 2009a,b) of the fact that spiral galaxies exhibit scale-invariant density fluctuations that extend to length-scales of $\sim 10$ kpc (e.g. NGC 628, NGC 1058) which is comparable to the diameter of the HI disc. While a large variety of possible energy sources like protostellar winds, supernovae, shocks, etc. have been proposed to drive turbulence (Elmegreen & Scalo 2004), it is still to be seen whether these are effective on length-scales as large as 10 kpc.

Galaxy harassment is expected to have different effects on the inner and outer parts of the galaxy. While gas is stripped from the outer parts, the inner part looses angular momentum and gradually collapses to the centre through repeated galaxy encounters. We can selectively study different parts of NGC 4254, whose rotation axis is tilted at 42$^\circ$ to the line of sight, by considering different velocity channels. Our analysis till now has used only the central 16 channels, we now use the central 24 channels (23–46) for the subsequent analysis. We construct three different data cubes namely A, B and C containing channels 23–30, 31–38 and 39–46, respectively. We can now separately probe the north-east, central and south-west parts of the galaxy (Fig. 3) using these three data cubes. For each data cube, we evaluate the HI power spectrum using individual channels and then average over the channels in the respective cubes. We estimated $U_m$ separately for A, B and C and the best-fitting power law is obtained for $U \geq U_m$ only. We find that for each data cube the HI power spectrum is well fit by a power law (Fig. 4), the details being shown in Table 1. We find that the slope $\alpha$ is $-2.0 \pm 0.3$ for A and C which probe the outer parts of the disc while it is $-1.5 \pm 0.2$ in B which probes the central region. To verify that this change in slope is due to harassment, we also consider the HI power spectrum of the spiral galaxies NGC 628 and NGC 1058 (Dutta et al. 2008, 2009a) which are not undergoing galaxy harassment. Fig. 5 shows

| Data            | Channels | $U_m$ (k$\lambda$) | $U$ range (k$\lambda$) | $\alpha$ |
|-----------------|----------|--------------------|------------------------|----------|
| 16 central      | channels |                    |                        |          |
|                 |          | 27–42              | 1.8                    | 2.5–10.0 | $-1.7 \pm 0.2$ |
|                 | A        | 23–30              | 1.3                    | 2.0–10.0 | $-2.0 \pm 0.3$ |
|                 | B        | 31–38              | 2.2                    | 2.5–10.0 | $-1.5 \pm 0.2$ |
|                 | C        | 39–46              | 1.3                    | 2.0–10.0 | $-2.0 \pm 0.3$ |

Figure 3. Integrated HI column density maps of the galaxy NGC 4254 using data cubes A, B and C. Note the diagonal movement of the centroid of emission from north-east (A) to south-west (C). The contours levels are 5.0, 8.0 and $12.0 \times 10^{20}$ atoms cm$^{-2}$.

Figure 4. HI power spectrum for data cubes A, B and C plotted with arbitrary offsets to prevent them from overlapping.
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Figure 5. Integrated HI column density maps of the galaxy NGC 628 using data cubes D, E and F. Note the diagonal movement of the centroid of emission from north-east (D) to south-west (F). The contours levels are 6.0, 12.0 and 18.0 \( \times 10^{20} \) atoms cm\(^{-2} \).

Figure 6. Power spectra of the HI emission for the galaxy NGC 628 is shown for D (channels 108–119), E (channels 120–131) and F (channels 132–143) with arbitrary offsets to prevent them from overlapping. Details of the data used for this estimation can be found in Dutta et al. (2008).

We find that the power spectra of these three data cubes (Fig. 6) all have the same slope \( \sim -1.6 \), which is also similar to the slope of the central part of NGC 4254. The results are similar for NGC 1058 and hence we do not explicitly show these here. Based on this we conclude that the difference in slope between the inner and outer parts of NGC 4254 is a consequence of galaxy harassment. Not only does galaxy harassment affect the global morphology of the galaxy, it also affects the fine scale structure in the ISM as reflected by HI power spectrum.

We note that NGC 4254 have an inclination of 42\( ^\circ \), on the other hand NGC 628 and NGC 1058 are more face-on galaxies (inclination \( \sim 10^\circ \)). In our analysis we selectively study different parts of a galaxy by considering different velocity channel ranges. However, since face-on galaxies do not have much range in radial velocity from the rotation curve, the spatial extent of HI in NGC 628 and NGC 1058 will not be very different for the three-velocity channel ranges, which is unlike the case for NGC 4254. Hence it is likely that we failed to find a change of slope in NGC 628 and NGC 1058 because of this effect of inclination. However, as seen in Fig. 5 for NGC 628, all three data cubes D, E and F have a significant contribution of HI from the outer region of NGC 628, leading us to believe that the power spectrum has a slope of \( \sim 1.6 \) in the outer parts of NGC 628. This is similar to the value of slope seen in the central parts of NGC 4254 and significantly different from the slope in the outer parts of NGC 4254. Hence it indicates an impact of harassment in NGC 4254. Further analysis of spiral galaxies with large inclination angles would possibly be able to resolve this issue.

We currently do not have an understanding of how galaxy harassment caused a steepening of the HI power spectrum in the outer parts of the galaxy. Theoretical modelling and the analysis of other Virgo cluster spiral galaxies are needed for further progress in this direction.

ACKNOWLEDGMENTS

PD is thankful to Sk. Saiyad Ali, Kanan Datta, Tapomoy Guha Sarkar, Tatan Ghosh, Suman Majumder, Abhik Ghosh, Subhasis Panda and Prakash Sarkar for useful discussions. PD would like to acknowledge HRDG CSIR for providing financial support. SB would like to acknowledge financial support from BRNS, DAE through the project 2007/37/11/BRNS/357. The data presented in this Letter were obtained from the National Radio Astronomy Observatory (NRAO) data archive. The NRAO is a facility of the US National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

REFERENCES

Begum A., Chengalur J. N., Bhardwaj S., 2006, MNRAS, 372, L33
Crovisier J., Dickey J. M., 1983, A&A, 122, 282
Davies J. et al., 2004, MNRAS, 349, 922
Deshpande A. A., Dwarakanath K. S., Goss W. M., 2000, ApJ, 543, 227
de Vaucouleurs G., de Vaucouleurs A., Corwin H. G., Jr, Buta R. J., Paturel G., Fouque P., 1991, Sky Telescope, 82, 621
Dutta P., Begum A., Bharadwaj S., Chengalur J. N., 2008, MNRAS, 384, L34
Dutta P., Begum A., Bharadwaj S., Chengalur J. N., 2009a, MNRAS, 397, L60
Dutta P., Begum A., Bharadwaj S., Chengalur J. N., 2009b, MNRAS, 398, 887
Elmegreen B. G., Scalo J., 2004, ARA&A, 42, 211
Elmegreen B. G., Kim S., Staveley-Smith L., 2001, ApJ, 548, 749
Green D. A., 1993, MNRAS, 262, 327
Haynes M. P., Giovanelli R., Kent B. R., 2007, ApJ, 665, L19
Lockman F. J., Hobbs L. M., Shull J. M., 1984, BAAS, 16, 981
Mei S. et al., 2007, ApJ, 655, 144

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Minchin R. et al., 2005, ApJ, 622, L21
Moore B., Katz N., Lake G., 1996, ApJ, 457, 455
Narayan C. A., Jog C. J., 2002, A&A, 390, 35
Phookun B., Vogel S. N., Mundy L. G., 1993, ApJ, 418, 113
Scalo J., Elmegreen B. G., 2004, ARA&A, 42, 275
Stanimirovic S., Staveley-Smith L., Dickey J. M., Sault R. J., Snowden S. L., 1999, MNRAS, 302, 417
Stutzki J., Bensch F., Heithausen A., Ossenkopf V., Ziellinsky M., 1998, A&A, 336, 697
Vollmer B., Huchtmeier W., van Driel W., 2005, A&A, 439, 921
Wouterloot J. G. A., Brand J., Burton W., Kwee K. K., 1990, A&A, 230, 21

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