Probing Kolmogorov turbulence beyond the Magellanic Clouds: The Power of Southern Hemisphere’s largest optical telescope (11m), SALT

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Abstract. The Hubble classification scheme of galaxies is based on blue-light appearance. Atlases reveal the rich variety of responses of the Population I component (‘the mask’) of gas and dust to the underlying, older, stellar population. However, the Population I component may only constitute 5 percent of the dynamical mass of the galaxy; furthermore, dusty masks are highly effective in hiding bars. We firstly discuss the rich duality in spiral structure, and highlight a near-infrared classification scheme for spiral galaxies. We next show that images secured with SALTICAM will be ideally suited to probe key questions such as whether the optical light in the gaseous Population I component is the result of Kolmogorov turbulence, cascading from the largest of scales down to the Nyquist limit. If so, the optical emission in galaxies will be organized in a global fractal pattern with an intrinsic 1D power spectrum having a slope of -5/3, or -8/3 in 2D.

1. Introduction

In Roget’s Thesaurus, we find the following:

Mask: [noun] screen, cloak, shroud. [verb] to camouflage, to make opaque, to disguise.

Optically thick dusty domains in galactic disks can completely camouflage or disguise underlying stellar structures. Cosmic dust grains act as masks. The dust masks obscure whether or not the dust lies in an actual screen or is well intermixed with the stars. The presence of dust and the morphology of a galaxy are inextricably intertwined: indeed, the morphology of a galaxy can completely change once the Population I disks of galaxies – the masks – are dust penetrated (e.g., Block and Wainscoat 1991; Block et al., 1994, 2000).
Figure 1. The bar in the Large Magellanic Cloud is beautifully portrayed in this naked eye drawing by Sir John Herschel in 1847. Two dimensional power spectra of HI emission in the LMC, spatially spanning three orders of magnitude, betrays the presence of Kolmogorov turbulence (Elmegreen, Kim and Staveley-Smith, 2001), with a power law slope of -8/3. SALTICAM will provide unique opportunities to examine Kolmogorov turbulence in galaxies beyond the Magellanic Clouds. Reproduced from de Vaucouleurs & Freeman (1972).
The classification of galaxies has traditionally been inferred from photographs or CCD imaging shortward of the 1$\mu$m window, where stellar Population II disks are not yet dust-penetrated. Images through an $I$ (0.8 $\mu$m) filter can still suffer from attenuations by dust at the 50% level. The NICMOS and other near-infrared camera arrays offer unparalleled opportunities for deconvolving the Population I and II morphologies, because the opacity at $K$ – be it due to absorption or scattering – is always low. The extinction (absorption+scattering) optical depth at $K$ is only 10% of that in the V-band.

Many years before the advent of large format near-infrared camera arrays, it became increasingly obvious from rotation curve analyses that optical Hubble type is not correlated with the evolved Population II morphology. This was already evident in the pioneering work of Zwicky (1957) when he published his famous photographs showing the ‘smooth red arms’ in M51. In the *Hubble Atlas* and other atlases showing optical images of galaxies, we are looking at masks: at the gas, not the stars, to which the properties of rotation curves are inextricably tied.

### 2. A duality in spiral structure

There is a fundamental limit in predicting what an evolved stellar disk might look like (Block et al. 2000). The greater the degree of decoupling, the greater is the uncertainty. The fact that a spiral might be flocculent in the optical is very important, but it is equally important to know whether or not driving the dynamics is a grand design old stellar disk.

Decouplings between stellar and gaseous disks are cited in many studies including Grosbol & Patsis (1998), Elmegreen et al. (1999), Block et al. (2000) and Puerari et al. (2000). The Hubble type of a galaxy does not dictate its dynamical mass distribution (Burstein & Rubin 1985). This is confirmed by examining Fourier spectra, for example, of the evolved disks of NGC 309 (Sc) and NGC 718 (Sa); these spectra are almost identical (both belong to pitch angle type $\beta$: see Table 1 and Fig. 5 in Block and Puerari 1999).

Figure 2 shows how the stellar disks of galaxies can quantitatively be classified in a systematic way.

### 3. Power Spectra and Kolmogorov Turbulence

One of the major processes which structures the interstellar media in galaxies is mechanical feedback: for example, supersonic winds from massive stars and multiple supernovae from OB associations. Such mechanical feedback may generate wind-blown bubbles (e.g. the Rosette: Block, 1990). Supernovae remnants as well super-bubbles (in both ionised as well as neutral gas) are two other well known examples.

The other major process that structures the interstellar medium on scales of 10 to $\sim$ 500 pc is turbulence. The standard reference for turbulent power spectra is the Kolmogorov model, applicable to homogeneous, isotropic, incompressible and adiabatic turbulence.
Figure 2. Spiral galaxies in the dust penetrated regime are binned according to three quantitative criteria: $H_m$, where $m$ is the dominant Fourier harmonic (illustrated here are the two-armed H2 family); the pitch angle families $\alpha$, $\beta$ or $\gamma$ and thirdly the bar strength, derived from the gravitational torque (not ellipticity) of the bar. Early type b spirals (NGC 3992, NGC 2543, NGC 7083, NGC 5371 and NGC 1365) are distributed within all three families ($\alpha$, $\beta$ and $\gamma$). Hubble type and dust penetrated class are uncorrelated. One of the enormous potentials of an infrared imager on SALT will be to examine whether spiral instabilities in stellar disks are fractal in nature.
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There are, at present, no good theories about the morphology of density structures in compressible turbulence; compressible turbulence gives a range of structures between incompressible turbulence and shocks. In a medium that is supersonically turbulent, the 2D power spectrum slope changes from $-8/3$ (-2.67) to -3; it is very difficult, therefore, to distinguish incompressible from shock dominated turbulence, as the differential signature is not large. Even the most extreme cloud formation scenarios, where all clouds represent shocks, would have a power spectrum similar to that of the classic Kolmogorov incompressible model.

Self-gravitating clouds of gas have a wide range of masses, from $\sim 10^7 M_\odot$ to less than $1 M_\odot$. There is no characteristic or dominant mass for self-gravitating clouds: most star-forming regions are similar, except for size. It is size which determines the velocity dispersion of the cloud, as well as its density, for a common background pressure.

The correlated structure in a turbulent gas is with a power spectrum:

$$\hat{I}_c(k) = \sum_{n=1}^{N} \cos(k2\pi n/N)I(n)$$

$$\hat{I}_s(k) = \sum_{n=1}^{N} \sin(k2\pi n/N)I(n)$$

$$P(k) = \hat{I}_c(k)^2 + \hat{I}_s(k)^2$$

$N$ is the number of pixels in the azimuthal scan and $k$ is the wavenumber. Two dimensional power spectra of the neutral hydrogen (HI) emission of the Milky Way (e.g. Green, 1993; Dickey et al. 2001) are characterised by power laws, with slopes varying from -2.8 to -3. Elmegreen, Kim and Staveley-Smith (2001) probed spatial scales in the Large Magellanic Cloud, ranging over three orders of magnitude (30-4000pc), and found a 2D power law slope to be $\sim -2.7$ (or equivalently -1.7 in 1D). Velocity and density spectra of the Small Magellanic Cloud are presented by Stanimirovic and Lazarian (2001); the spectral indices (for their 3D power spectra) are -3.3 and -3.4, equivalent to a 1D power law slope of -1.4.

For classical Kolmogorov turbulence, the implication is that the gas is fractal in nature, with the turbulent kinetic energy cascading to ever smaller scales, according to $E(k)\propto k^{-5/3}$. This derives from the assumption of a constant energy transfer at at scales. Values steeper than -5/3 signify progressive energy losses, such as from compressible or shock dominated turbulence.

If the scale height in the ambient medium is the typical scale for coherent star-forming structures, then self-gravity in the gas initiates the formation of star-forming clouds and star complexes (see Figure 3). Why use power spectra instead of conventional 2D Fourier transforms? For galaxies, the 2D Fourier transform includes structure from the exponential disk, which is generally not wanted in analyses of interstellar clouds. Power spectra generated from azimuthal profiles are, however, ideal, since in any given azimuthal swath, there will be no systematic radial gradients from the disk.

Elmegreen, Elmegreen and Leitner (2003) have studied some famous examples of nearby spirals (such as NGC 3031=M81), and have generated power
Figure 3. Forty-eight power spectra are generated from this HST image of the Sb galaxy NGC 4622. The galaxy was analysed in circular swaths, from a galactocentric radius of \( r = 10 \) to \( r = 490 \) pixels. The first circular swath covers \((10, 19)\) pixels, the second one \((20, 29)\) pixels, ..., \((480, 489)\) pixels. Adopting a distance to NGC 4622 of 45.02 Mpc and using a HST/WFPC2 scale of 0.09993 arcsec pix\(^{-1}\), gives a linear scale of 21.81 pc per pixel. The mean radius corresponding to the lowermost power spectrum is 15 pixels (or 0.327 kpc); that of the uppermost, 485 pixels or 10.577 kpc. Each power spectrum contains Fourier modes \( k = 1 \) to \( k = 1800 \). We have multiplied each power spectrum by \( k^{5/3} \) so that power spectral slopes of \(-5/3\) will appear horizontal here. Of particular interest is the \(-5/3\) power law slope within the domain of the probable thickness of its galactic disk (for the Milky Way, this is 325 pc). As soon as structures are formed with sizes comparable to, or smaller than, the disk thickness, the dynamics in the plane and vertically to it are no longer independent (see, e.g., Huber and Pfenniger, 2001). HST image courtesy R. Buta.
spectra of the optical light in passbands such as B, V and R. Their conclusion is that the optical light in spiral galaxies (even grand-design ones such as M81) is the result of turbulence; the implication therefore, is that young stars follow the gas as they form. They argue that large-scale turbulent motions may well be generated by sheared gravitational instabilities in the disk.

SALT will yield the much needed insight into the physical scale at which star formation in galaxies becomes coherent; in our Galaxy, we know this may range from several hundred parsecs, to a kpc (Gould’s belt, of age $\sim 30$ Myr, spans $\sim 1$ kpc).

Its optical imager, SALTICAM, with its default BVRI filters and $10 \times 10$ arcmin field of view, coupled with its high spatial resolution ($15 \mu m$ pixels, $106.7 \mu m$ arcsec$^{-1}$, $\sim 7$ pixels per square second of arc), will be ideally placed for exploring Kolmogorov turbulence beyond the Magellanic Clouds, down to the Nyquist limit.

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References

Block D.L. 1990, Nature, 347, 452
Block D.L. & Wainscoat R.J. 1991, Nature, 353, 48
Block D.L. et al. 1994, A&A, 288, 365
Block D.L. & Puerari I. 1999, A&A, 342, 627
Block, D.L. et al. 2000, ‘Toward a New Millennium in Galaxy Morphology’ (eds. D.L. Block, I. Puerari, A. Stockton & D. Ferreira, Kluwer); see also Ap&SS, 269, 5
Burstein D. & Rubin V. 1985, ApJ, 297, 423
Buta, R.J. & Combes, F. 1996, Fund. Cosmic Phys. 17, 95
Buta, R.J. & Block, D.L. 2001, ApJ, 550, 243
de Vaucouleurs, G. & Freeman, K.C. 1972, Vistas in Astronomy, 14, 163
Dickey, J.M. et al. 2001, ApJ, 561, 264
Elmegreen, B.G., Kim, S. & Staveley-Smith, L. 2001, ApJ, 548, 749
Elmegreen, B.G, Elmegreen, D.M. & Leitner, S.N. 2003, ApJ, 590, 271
Elmegreen, D.M. et al. 1999, AJ, 118, 2618
Green, D.A. 1993, MNRAS, 262, 327
Grosbøl, P.J. & Patsis, P.A. 1998, A&A, 336, 840
Huber, D. & Pfenniger, D. 2001, A&A, 374, 465
Puerari, I. et al. 2000, A&A, 359, 932
Stanimirovic, S. & Lazarian, A. 2001, ApJ, 551, L53
Zwicky, F. 1957, ‘Morphological Astronomy’, Springer-Verlag, Berlin.
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