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STUDIES OF TURBULENCE IN GASEOUS NEBULAE

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RESUMEN

En este trabajo discutimos las evidencias de la existencia de turbulencia hidrodinámica en nebulosas gaseosas. Presentamos los métodos de análisis estadístico de campos de velocidad radial y evaluamos los resultados disponibles en la literatura. Como ejemplo, presentamos un análisis del campo de velocidades en la región H II gigante NGC 595, utilizando la función de estructura. Los datos de la cinemática de la región fueron obtenidos utilizando TAURUS-2, un interferómetro Fabry-Perot en operación en el Observatorio del Roque de los Muchachos. Hemos encontrado una correlación entre las diferencias cuadráticas medias de velocidades radiales y la distancia sobre la superficie de la nebulosa a pequeñas escalas. El modelo de Kolmogorov se compara con los resultados observacionales y discutimos su validez.

ABSTRACT

We discuss in this work the evidence for the existence of hydrodynamical turbulence in gaseous nebulae. The methods for the statistical analysis of the velocity fields are presented, and the results available in the literature are discussed. As an example, we present an analysis of the velocity field of the giant H II region NGC 595, using the structure function. The radial velocity data were obtained using TAURUS-2, a Fabry-Perot imaging spectrograph at the Observatorio del Roque de los Muchachos. We find that there is a correlation between the mean quadratic differences of radial velocities and distance over the surface of the nebula at small scales. The standard Kolmogorov model for turbulence is examined and compared with the observations.

Key words: **H II REGIONS — TURBULENCE**

1. INTRODUCTION

The combination of observational data from Fabry-Perot and Echelle systems, and the most sophisticated numerical models that describe the evolution of gaseous nebulae, shows that the velocity structure of H II regions is extremely complex, with the observations indicating mass motions that can be attributed to a chaotic component. This component in the velocity field can be a manifestation of turbulence, that can be understood as random motions in a fluid; a collection of eddies (elements of turbulence) forming and dissolving on a great variety of scale lengths (Kaplan 1966; Tennekes & Lumley 1972).

What is usually understood as turbulence is the difference resulting from the subtraction of the instrumental and thermal broadening from the observed emission line width; it is a quantity that represents the contribution due to macroscopic motions of the gas. In the case of giant extragalactic H II regions it has been observed that the non-thermal contribution to the line widths of the emission lines is larger than the sound speed of the gas. The existence of pressure gradients should move the gas to velocities of the order of the sound speed (~ 10 km s^{-1}), so extra forces such as gravitation and stellar winds may play a role as sources of the observed

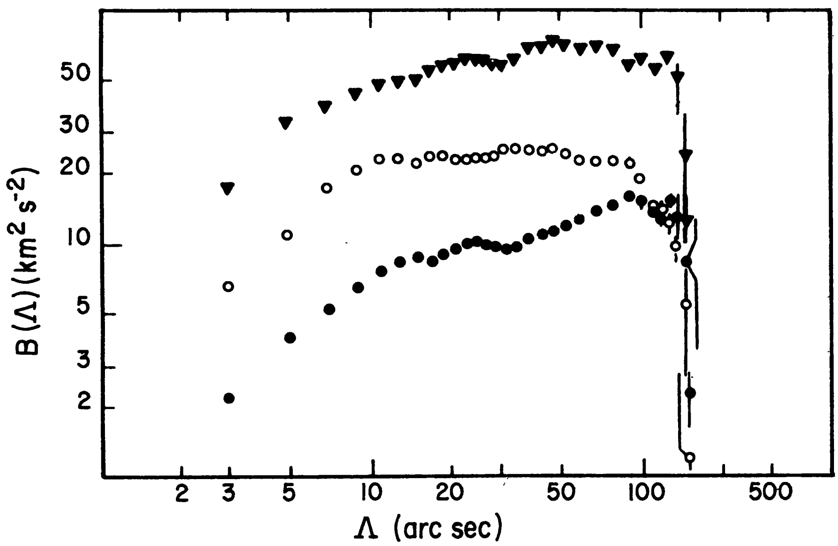

Fig. 1. Structure function for the three main components of the velocity field in [O III] for the Orion Nebula (from Castañeda 1988).

motions. Whatever mechanism is driving the motions of the gas, it is clear from the observations that an important component in the velocity field of the gas is random.

The problem then, is to establish if this component to the motion of the gas can be understood as the result of hydrodynamical turbulence. In the statistical approach to the study of turbulence there is a manifestation of the statistical order in the flow in the velocity field, which allows the prediction of the general behavior of the fluid with the use of statistical techniques like averages and correlations of different physical quantities (Scalo 1984). The existence of turbulence is confirmed by the presence of correlations in physical parameters such as density, pressure or velocity, that can be detected by means of statistical functions, for which the structure function is ideally suited. The structure function is defined as the average of the quadratic differences of velocities as a function of the spatial separation between the points where the velocity is measured (see Castañeda 1988).

2. STUDIES IN GALACTIC AND EXTRAGALACTIC H II REGIONS

Studies concerning the determination of the structure function in gaseous nebulae have been done for the main H II regions of our Galaxy and in general it can be concluded that while there is a dependence of random velocities upon scales, there is no single power law for the observed structure function that fits the observations, suggesting the injection of energy at different scales of motion. We show in Figure 1 an example of the observed correlations for the Orion Nebula.

Very few works (with relatively old data) have been done along these lines on giant extragalactic H II regions. For example, Melnick et al. (1987) used the data of Smith & Weedman (1972) to compute the structure function in 30 Doradus and claimed that there was no effect of coherent motions in the nebula. Clearly a systematic study of the statistical properties of the velocity field of Giant Extragalactic H II Regions (GEHRs) is necessary. Such a study is now possible, since modern spectroscopic techniques, including Fabry-Perot imaging spectroscopy, provide in a single integration a complete velocity map for the regions (seeing limited) with high velocity resolution. To study the process of turbulence in these giant complexes, we are conducting a detailed study of the radial velocity field for the largest H II regions studied in the survey on the kinematic properties of GEHRs described in the paper by Castañeda et al. (1995). As an example of the results obtained, we describe results from the study of NGC 595.

2.1. A Case Study: The Structure Function of NGC 595

The region NGC 595 is the second largest H II region in M 33 (720 kpc away from the Milky Way). It is an evolved ($\sim 5 \times 10^6$ yr) region, with several emitting knots and a large inhomogeneous halo. While there are

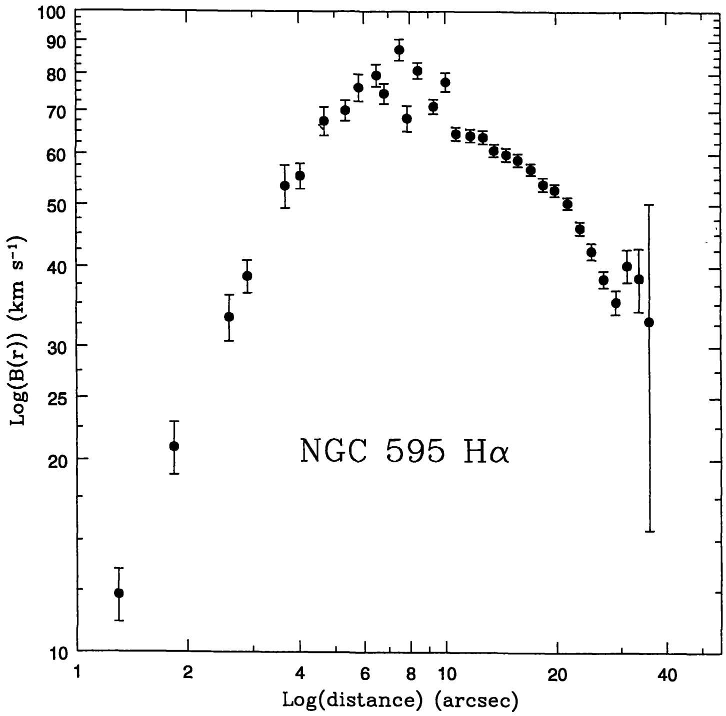

Fig. 2. Structure function for NGC 595 in Hα. The function has been calculated after corrections for large scale motions.

no supernova remnants found within the region, Wolf-Rayet stars have been detected. The region was observed with TAURUS-2 in Hα with a 3600 sec integration. The data cube was 256 × 256 in the spatial scale (0.26 arcsec pixel^{-1}), and 100 planes (steps) in the wavelength dimension, with a spectral scale of 9 km s^{-1} per plane. The calibrated data cubes produced maps of the peak intensity, line width (sigma value) and radial velocity at each position, which were subsequently used as masks to eliminate fits with low S/N, as well as spectra where the line width was smaller than the instrumental line width. The velocity map was corrected for systematic motions before computing the structure function.

The structure function was computed by the selection of all possible pairs of points within a given sample size ($\Lambda - \Delta \leq \Lambda \leq \Lambda + \Delta$), where Λ is the angular separation between points, and (2Δ) the bin size. Finally, the function was corrected for instrumental dispersion.

In Figure 2 we show the results of the computed structure function for NGC 595. In the plot, the structure function is shown as log B(Λ) vs. log (Λ). We have done linear least-squares fits of the slope in the range where there is correlation of the results, using a power law of the type $B(\Lambda) = M\Lambda^n$. For the scales $\Lambda \leq 8$ arcsec, (26 pc) the structure function shows a definite correlation, with n = 1.40 ± 0.02, (correlation coefficient of 0.999). We found very similar exponents for the structure functions of the other GEHRs studied (Castañeda, Fuentes-Masip, & Helmi 1995). For NGC 595 there is a decorrelation on scales ≥ 26 pc, and it can be argued that this value represents a characteristic physical length of the system, for example the length corresponding to the size of the largest eddies. The next step is to compare the results with the predictions of the theory.

3. COMPARISON WITH THE THEORY

If the velocity field is homogeneous and isotropic, the structure function depends only on the absolute separation between the points (r). In the case of the Kolmogorov law, the relation between the quadratic velocity difference between two points (v^2) and their distance (r) is $v^2 \sim r^{2/3}$ (Kolmogorov 1941).

The problem of understanding the effect of projection for a correlation in three dimensions over a bi-dimensional area (the surface of the object) was addressed originally by von Hoerner (1951) and generalized by O'Dell & Castañeda (1987). It can be shown that the relation between velocity differences and the separation over the surface of the nebula is geometry dependent. Given a Kolmogorov spectrum of slope 2/3, a plane-parallel model predicts that projection smearing will produce a correlation function with a spectral index of 5/3, if Λ (the separation between two points over the surface of the H II region) is $\ll$ R (the depth of the cloud), and 2/3 when $\Lambda \gg$ R. The form of the solution for a correlation $v^2 \sim r^{2/3}$ is (Castañeda 1988):

$$v^2 = B(\Lambda) = C^2\Lambda^{2/3}2\mathbf{l} \int [\, (1+x^2)^{1/3} - x^{2/3}]\, (1 - \mathbf{l}x)\, dx \,,$$

where $\mathbf{l} = \Lambda/R$, C is a constant, and the limits of the integral are $(0; 1/\mathbf{l})$.

Exponents on the order of $\sim$-1.45 are predicted in the observed structure function for scales of $\mathbf{l} \sim 0.05$. Therefore, the observed slope is compatible with the predictions of the simple plane-parallel model for hydrodynamical turbulence for scales small compared with the size of the nebula. A different behavior is observed in galactic H II regions, in which the slopes of the structure function are flatter than expected. For example, for the Orion Nebula the exponents of the correlations are on the order of 0.9 − 1.2. This indicates that the integration depth along the line of sight is of the same order as the separation between points.

As stated before, in the plane-parallel model we should see an asymptotic behavior of the structure function to a slope $n \sim 2/3$. Instead we see a clear decorrelation of the function. Several possibilities that could explain the behavior of the function are being examined. For example, the model does not consider energy injection into the nebula at different scale lengths, a factor that could change the slope of the function. A more severe problem that can change the form of the structure function is that, since we are observing the velocity averaged along the line of sight, the velocity is weighted by the local intensity (emissivity). Thus, changes in the emissivity and the excitation can introduce an extra correlation. The emissivity is not constant over the region, as we know from the fact that the filling factor of giant H II regions is $\ll 1$, while an implicit assumption in the model is that the emission is constant along the path of integration. Other factors that could change the form of the function and make more difficult the interpretation of the results are the intermittence of the energy injection, compressibility of the medium and dissipation mechanisms, heavy extinction, anisotropy of the velocity field, and inhomogeneity of the flow.

After we have examined the nature of the velocity field over the regions and compared the results with the theory, what remains to be understood is the source of turbulence, and its implications for the form of the observed structure function. In the standard Kolmogorov model, the energy spectrum of turbulence becomes dependent only on ϵ, the mean dissipation of energy per unit time per unit mass of fluid, with the inertial forces transferring kinetic energy from larger to smaller turbulent elements. If L is the characteristic length of the largest eddies, and Δu the typical velocity dispersion, we have $\epsilon = (\Delta u)^3/L$. In an equilibrium state, the rates of energy input and energy dissipation should be equal. If we postulate, for example, that stellar winds are the main source for the turbulent motions observed, the available models that predict the energy inputs of mass, momentum, and energy from stellar winds, together with the typical values of the velocity dispersion for the region, can be used to estimate a "typical" value of L, that can be compared with the scale of decorrelation observed in the structure functions in different nebulae and to check their agreement.

4. CONCLUSIONS

Our results indicate the presence of turbulence in NGC 595, as shown by the statistical correlations seen in the structure function. There is no complete agreement with a simple plane-parallel model , although the slope at small scales is compatible with the Kolmogorov model. A new model is necessary, that includes both the possibility of injection of energy at different scales as well as the non-constant emission of the medium. A similar behavior of the structure function has been found for other GEHR and will be the subject of a forthcoming paper.

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