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EMISSION LINE RATIO MAPPING WITH OSIRIS

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RESUMEN

Explicamos brevemente dos aplicaciones complementarias del filtro sintonizable de OSIRIS para investigar galaxias externas: diagnóstico del gas difuso ionizado en objetos observados de cara y de canto, ilustrando los objetivos con galaxias cercanas, y discutiendo observaciones previstas para "redshift" intermedio y alto.

ABSTRACT

We outline two complementary applications of the tunable filter system in OSIRIS for research on external galaxies: diagnostics of the diffuse ionized gas in face-on and in edge-on objects, giving illustrations for nearby galaxies, and discussing projected observations at intermediate and high redshift.

Key Words: **GALAXIES: ISM — GALAXIES: SPIRAL — ISM: GENERAL — (ISM:) H II REGIONS — ISM: LINES AND BANDS**

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1. THE OSIRIS TUNABLE FILTER: ITS GREAT ADVANTAGES FOR EXTRAGALACTIC RESEARCH

The presence of a tunable narrow band filter as part of the OSIRIS instrument on the 10.4 m GTC will provide unique opportunities in the field of extragalactic research. The physics of the ionized gas and its distribution within the structure of individual galaxies, and in the intergalactic medium in clusters, with its indirect information about local and global star formation rates, are among the most relevant fields of use. In the short term our understanding of the evolution of individual local galaxies will receive a strong impulse, and in the medium term we will be able to apply the same techniques to individual galaxies and also to clusters at medium and high redshift. The potential of the instrument lies in its ability to tune a narrow passband to an arbitrary optical wavelength. This enables the user to image an extended object in a narrow spectral range, which could be that of an emission line at an arbitrary redshift, or that of an absorption line population index. In the present article we look at one specific type of application, based on results already beginning to emerge from nearby galaxies using 4 m class telescopes: the exploration of the diffuse ionized gas both close to the central plane of a galaxy, and away from the plane into the halo. This gas is not as spectacular as the ionized medium in H II regions, but as with many astrophysical "backgrounds" it contains extremely valuable information, in this case about the conditions in the general interstellar medium of galaxies and about the disk–halo transition.

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2. THE EMISSION FROM THE IONIZED GAS PROJECTED INTO THE PLANE OF A GALAXY

In Figure 1 (right) we show the distribution of the emission of the diffuse ionized gas from the plane of a typical disk galaxy, observed in Hα, using the classical narrow band filter technique of imaging though a filter centered on the line, then through a filter at a neighboring wavelength of approximately equal passband to obtain the stellar continuum contribution, and subtracting off the continuum from the line + continuum to yield a map of surface brightness in the emission line. Using standard flux calibration techniques a map of this type can be obtained in calibrated surface brightness units. We can see immediately the two main morphological components of this image: the localized H II regions, with their high surface brightness, and the substrate of diffuse emission which covers the full face of the galaxy. We have used images of this kind to study the internal physics of H II regions (Cepa & Beckman 1990a; Knapen et al. 1992; Rozas et al. 1996a, 1996b, 1998a, 1999, 2000; Beckman et al. 2000), the mechanism of ionization of the diffuse gas (Zurita, Rozas, & Beckman 2000, 2001; Zurita et al. 2002) and aspects of star formation in spirals (Cepa & Beckman 1990b; Knapen et al. 1992; Rozas et al. 1998b). We should point out that these references are to articles which describe observations only in Hα, without reference to the use of images in any other spectral line, or to three-dimensional imaging in intensity and velocity using scanned Fabry–Perot instruments.

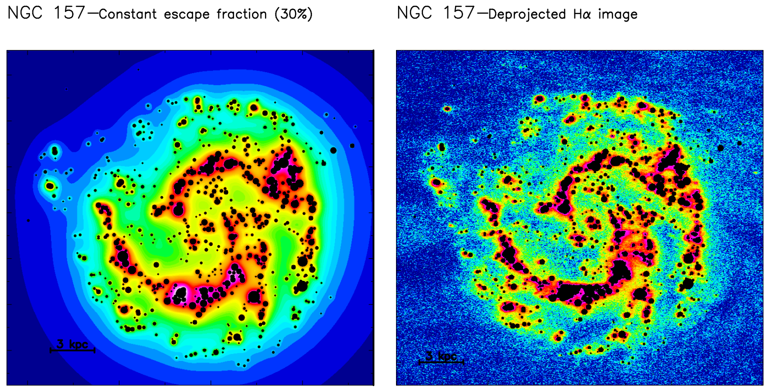

Fig. 1. Deprojected Hα emission of the observed diffuse ionized gas of NGC 157 (right), compared to predicted Hα surface brightness (left) from a model in which the diffuse gas is photoionized by photons escaping from the H II regions (for details see Zurita et al. 2002).

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As far as the diffuse emission is concerned, we have established observationally that the integrated luminosity of the diffuse component in a typical disk galaxy is of order 50% of its total emission in Hα. (Zurita et al. 2000), and that its surface brightness distribution can be rather well reproduced using the assumption that its principal cause is ionizing photons escaping from H II regions (see Zurita et al. 2002 for a discussion which includes detailed modeling, taking into account the H I distribution). However, there are a number of issues outstanding, which can be answered only via photometric mapping in a number of emission lines and line ratios. The main question to address for the diffuse emission is whether it can be accounted for wholly or principally by photoionization, in other words by photons from OB stars (because the ionizing luminosity output from white dwarfs falls short by over an order of magnitude) or whether there is an important element of shock ionization. Apart from the possibility of detecting clear shock fronts via abrupt spatial rises in local temperature and electron density, maps in the principal emission lines due to O I, O II, and O III, to to N II, and to S II and S III will give us the tools we need to make observational distinctions between the two mechanisms across the full face of a galaxy. Line ratio variations, spatially mapped, are the key to this and to many other diagnostics, both in the diffuse gas and within H II regions. We can summarize some of the main possibilities as follows:

- Electron temperature: ratios of lines of different ionization states of O.
- Electron density: line ratios for doublets of S II and N II.
- Dust optical depth distribution: ratios of Balmer line intensities; ratios between lines of Fe II and Fe III.
- Star formation rates: Hα maps, corrected for dust distribution and ionizing photon escape factor.
- Morphological distribution of star formation and its relation to other gaseous and stellar features of the galaxy: corrected Hα maps.

If we take into account the fact that all these types of measurements will be available from an arbitrary face-on disk galaxy, owing to the tunability of the system, and that even the weakest lines, which are needed for good electron temperature estimates, will be measurable during a single night with a 10m telescope, it is clear that the OSIRIS TF will be an instrument of unique power for resolving the problems listed. As a bonus (which for some workers would be the most important result), using these observations we would acquire the abundances of key elements (O, N, S and others) and their spatial distributions, notably their radial distributions, with a morphological accuracy not possible until now.

3. THE EMISSION FROM GAS IN EDGE-ON GALAXIES

Observing edge-on systems is a complementary method for obtaining structural information about spirals. This is of particular interest for the diffuse emission, since its scale height, of order 1 kpc or more in a Milky Way type system, is considerably

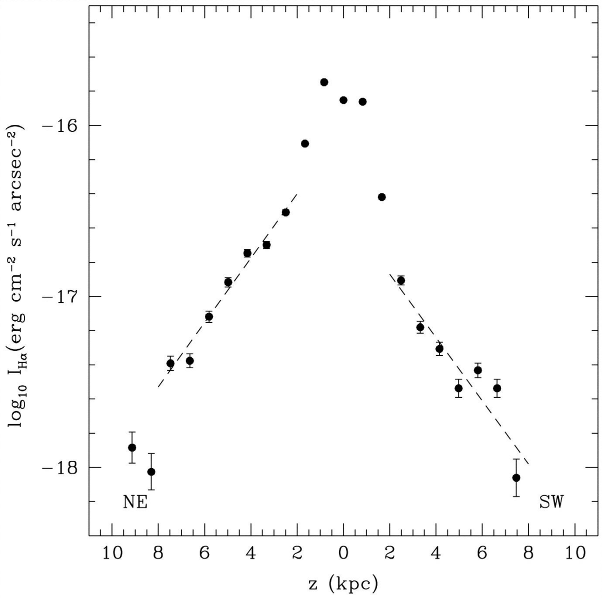

Fig. 2. Emission measure as a function of height above the plane for Hα in the edge-on galaxy NGC 5775. The in-plane emission is readily distinguishable from the out-of-plane diffuse emission, which has a clearly measurable scale height (from Collins & Rand 2001).

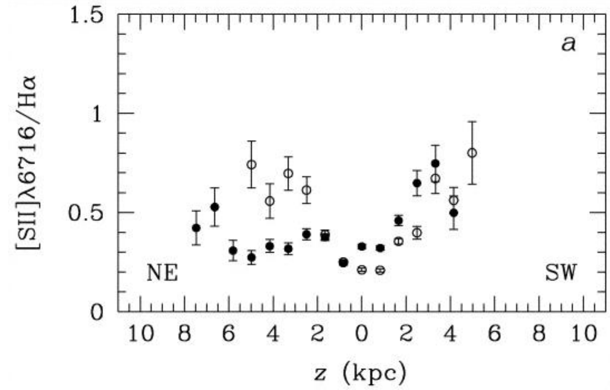

Fig. 3. Ratio of [S II]/Hα with height above the plane for NGC 5775 (from Rand 2000) for different slit positions (slit 1: filled circles; slit 2: open circles). This and similar diagnostics can be used to probe for shock and photoionization (see Figure 4).

bigger than that of the stellar populations, and of the neutral gas with its admixture of dust, which is typically of order 0.1–0.2 kpc. This means that one can obtain information about the vertical structure of the ionized layer, and under geometrically favorable conditions about its relation with sources of ionization. To illustrate the possibilities we will quote Rand (2000) and Collins & Rand (2001), who give particularly clear-cut examples of observations in a group of edge-on galaxies. They used classical slit spectroscopy to examine the behavior of the emitting gas perpendicular to the planes of these galaxies, out to distances of more than 5 kpc from the planes. The results of one of their objects illustrate the kind of observations which OSIRIS should enable us to obtain two-dimensionally, and which the GTC will enable us to extend further into the halo of a galaxy, since the data were obtained using a 4 m class instrument (the Kitt Peak 4.2 m). The first type of information obtainable is just the run of line intensity with height above the plane enabling one to calculate the scale height of the diffuse emission. In Figure 2 (from Collins & Rand 2001, their figure 5a) we show measurements of Hα emission for NGC 5775. From a slit perpendicular to the plane, at $\sim$2 kpc from the center to the SW. We can see the off-plane component, which is easy to separate from the emission close to the plane, using a direct slope fit to the off-plane gas. The interpretation is that the emission close to the plane is from a mixture of H II regions and diffuse gas, while that from more than 1 kpc off the plane is all from the diffuse component, which has a scale height of $\sim$2.5 kpc. The observations here run out to well over 8 kpc from the plane. It is not difficult to see that with OSIRIS a complete two-dimensional map of the Hα emission could be obtained for a galaxy of this type.

The second type of information available is of line ratios, and in Figure 3 (Rand 2000, their figure 2a) we show the ratio of a selected line of [S II] and its variation with distance from the plane, along the two slit positions. In Rand (2000) similar plots are shown for [N II]/Hα and for [O III]/Hα.

Our aim in this short paper is not to go into detail about these observations but to show how they can be used diagnostically, and what sort of information can be obtained. The slit positions on NGC 5775 were chosen to cross obvious bright filaments within the diffuse gas. The NE portion of slit 1 (see Figure 3) crossed a bright Hα filament known to be associated with an expanding shell in H I, most probably due to the expanding gas of a massive star forming region, while slit 2 was placed across a bright Hα plume associated with similar activity. The remaining portions of the slits passed across relatively fainter less featured gas.

In Figure 4 (from Collins & Rand 2001, their figurre 8) we show a diagnostic diagram in which [O III]/Hα is plotted against [N II]/Hα for filamentary and non–filamentary regions. The solid curve shows the prediction of a density-bounded photoionization model (Sokolowski 1994), as a function of ion-

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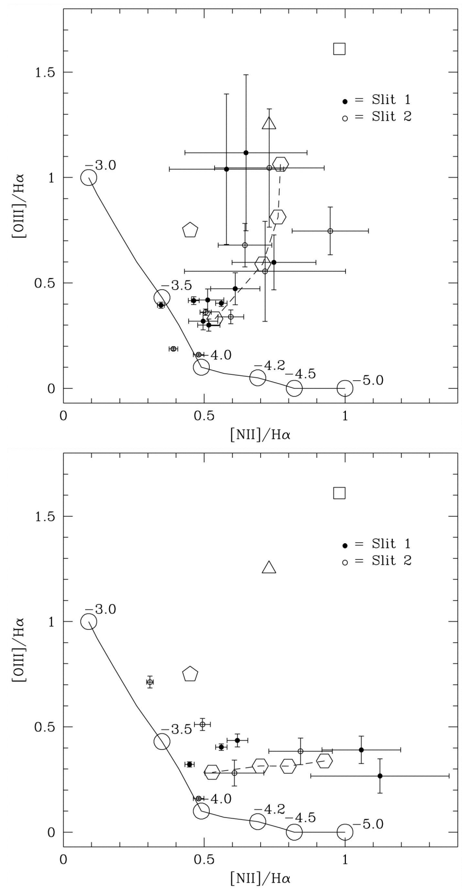

Fig. 4. Diagnostic diagrams to distinguish between photoionization and shock ionization in (top) an off-plane filament and (bottom) the general off-plane diffuse non-filamentary gas. Symbols are explained in the text. This and other equivalent tests (see Collins & Rand 2001, their figures 8–10) show clearly that shocks can predominate in filaments, but that photoionization dominates in the general diffuse gas.

ization parameter U, with numerical values shown. The triangles, squares and pentagons are the results of pure shock ionization models (Shull & Mckee 1979), and the hexagons are mixed models which in fact best fit the data. In the filaments the fraction of shock ionization varies from 20% at $U = -4$ to 80% at $U = -5$, while in the bulk of the gas the fraction ranges from 16% at $U = -4$ to 27% at $U = -5$. The conclusion is that in the bulk of the gas photoionization predominates, while in the filaments shock ionization is a major contributor. Similar conclusions can be drawn from diagrams in which [O III] is substituted by [S III], given in Collins & Rand (2001), and their plot of [O I]/Hα vs. [N II]/Hα, although reaching only to 2.5 kpc over the plane, confirms that a mixed model dominated by photoionization gives the best fit to the data.

The importance of the material presented here is that it enables us to explore a number of interesting aspects of the transfer of energy into the haloes of galaxies, and it should be clear how advantageous it would be to be able to take line ratios over the whole of the out-of-plane gas in a galaxy in a single set of photometric line images. One should not lose sight of the need for velocity information, which can be obtained either using H I emission, or a limited set of slit spectra to complement the OSIRIS data, but all of the diagnostics touched on here can be carried out with the OSIRIS TF, and in two dimensions instead of the single dimension slit approach.

4. THE EMISSION FROM GAS IN EDGE-ON GALAXIES

One of the by-products of the kinds of observations outlined is Sections 2 and 3 will be an estimate, much more reliable than at present, of the star formation rate (SFR) in a galaxy associated with a given integrated Hα luminosity. There are two types of corrections to apply to the initial data: that for the interstellar dust, which acts both on the ionizing photons and on the Hα itself, and that for the loss of ionizing photons into the local intergalactic medium. The first factor could be as much as a factor of two, while the second may not amount to more than 20%, but in any event they are not well determined at the present time. Estimates of these factors, and of their metallicity dependence, in local well-resolved galaxies will enable us to make improved estimates of star formation rates over ranges of z of cosmological interest, using principally OSIRIS + TF data, both in the context of the OTELO key project, and in more general terms. At redshifts greater than 1, the aim would be line imaging in clusters, and for intermediate and high z, Hβ would have to take over from Hα as the key SFR indicator, so that careful work in nearby objects would be needed to calibrate its loss factor, notably by absorption.

As well as observing more distant objects, linking morphology of interaction with shock diagnostics, using essentially the techniques outlined above, the same methods could be employed in an entirely different though strongly related project. Detection of Hα from high mass clouds of essentially neutral hydrogen in the circumgalactic zones of major galaxies will enable us to assess their importance as a fueling source for the major galaxies (also their increasing importance with z), and the application of shock vs. photoionization diagnostics will enable us to tell whether they can be used as ionization probes to measure the radiation field of the galaxy. For these measurements the full power of the 10.4 m instrument plus the full flexibility of the OSIRIS + TF will be essential.

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