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PHYSICAL CONDITIONS IN B2 RADIO GALAXIES

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RESUMEN

Reportamos un estudio de las propiedades del gas en emisión de radio galaxias débiles (WRG). Nuestras metas son mejorar el conocimiento acerca de las regiones emisoras extendidas en núcleos activos de galaxias y analizar las relaciones entre objetos con emisión en radio débil y potente. Obtuvimos imágenes en banda ancha y angosta de una muestra de galaxias del catálogo B2, con $P_{1.4GHz} < 10^{24.5}$ W Hz^{-1} y radio jets, para estudiar la morfología y las propiedades fotométricas, de los objetos. En este trabajo se presentan imágenes ópticas en $H\alpha +$[N II] y [O III], obtendidas con un CCD de gran formato, de algunas de estas radiogalaxias. Presentamos la luminosidad en línea, así como estimaciones de la densidad cuadrática media de los electrones y la masa del gas que está emitiendo.

ABSTRACT

The properties of the emitting gas in weak radio galaxies (WRG) are analyzed. Our goals are to improve the understanding of the extended emitting regions in AGNs and look for the relationships between objects with weak and loud radio emission. Images of a large sample of galaxies from the B2 survey, with $P_{1.4GHz} < 10^{24.5}$ W Hz^{-1} and radio jets, were obtained to analyze the morphology and the broad-band and narrow-band photometric properties. Optical CCD images of radio galaxies obtained at $H\alpha +$[N II] and [O III] are presented. We estimate the emission-line luminosity, the *rms* electron density and the total mass of the emission-line gas.

Key words: **GALAXIES: ACTIVE — GALAXIES: NUCLEI — GALAXIES: PHOTOMETRY — RADIO CONTINUUM: GALAXIES**

1. INTRODUCTION

It is now well known that some radio galaxies and radio-loud quasars have emission-line gas which is extended on scales of tens of kiloparsecs. In some radio galaxies there is convincing evidence that the ionization of the very extended emission-line gas is governed by its interaction with the outflowing radio plasma. However, in other radio galaxies the evidence for an interaction is much weaker. In these sources the ionization of the emission-line gas may be predominantly produced by the nuclear ultraviolet continuum while the kinematics of the gas is governed by the gravitational potential of the host galaxy, but it is not yet known whether there is a physical relationship between the emission-line gas and the extended radio-emitting plasma in these sources.

In this work we summarize some properties of the emitting gas obtained from an optical imaging study, based on broad-band (*V*, *R* and *I*) and narrow-band (redshifted $H\alpha +$[N II] $\lambda\lambda$6548, 6583 and [O III] λ5007) images of a selected sample of radio galaxies. We also use data available in the literature to study the relationship between the detected extended emission-line gas and the observed radio structures. Details of this study are presented in Carrillo (1995) and Carrillo, Cruz-González, & Guichard (1995a, b).

2. SAMPLE SELECTION

The observed sample consists of 26 galaxies identified with radio sources of the Second Bologna Survey (B2) (for details see Fanti et al. 1987). The chosen sources all have $P_{1.4GHz} < 10^{24.5}$ W Hz^{-1}, therefore all of them are weak radio galaxies (WRGs) of the type FR I (Fanaroff & Riley 1974). VLA studies of these galaxies provided us with information about radio luminosities, morphological properties, jet properties, and radio polarization. The selected galaxies satisfy the following criteria: to be members of B2 survey, to be sources with core and jet structure and to have low redshifts (z $\leq$ 0.07).

3. OBSERVATIONS AND DATA REDUCTION

CCD images with Hα + [N II] or [O III] filters, and broad-band filters (V, R and I) were obtained with the 2.1-m telescope of the Observatorio Astronómico Nacional at San Pedro Mártir, B.C., México. Details of the observations, image processing and the complete set of images obtained can be found in Carrillo (1995) and Carrillo et al. (1995a, b).

4. RESULTS

Emission-line gas was detected in all the observed sources. Our estimates of the total luminosities in Hα + [N II] or [O III] range from 1.3×10^{39} to 6.7×10^{41} ergs s^{-1}, which yields a mean value of $L_{line} \sim 1.1 \times 10^{41}$ ergs s^{-1}. These results should be confirmed spectroscopically in future work.

In 21 of the 26 sources in the sample, i.e., 81% of the sources, we have resolved the emission-line nebulae. The nebulae have sizes in the range from less than 1.6 up to 9.1 kpc, with a mean extent of ~ 4.6 kpc. The emission-line nebulae show different morphologies. In some sources we observe only small, centrally condensed, kpc scale "oval" type regions, while in others we detected much more extended filaments and complex structures. In Figure 1 (Plate 2) we show images of the emission-line nebulae found in B2 0331+39 (Hα + [N II]), B2 1339+26 ([O III]), and B2 1346+26 ([O III]), superimposed on the radio continuum maps from Fanti et al. (1987). In these images we note a wide variety of emission-line nebula morphologies and the close connection or alignment between the radio and emission-line structures.

From the comparison of the emission-line luminosities of WRGs with the line luminosities of normal elliptical and lenticular galaxies (~ 1.5×10^{39} erg s^{-1}; Phillips et al. 1986) and powerful radio galaxies (~ 3×10^{41} erg s^{-1}; Baum & Heckman 1989) we find that the line luminosities in WRGs appear to be one order of magnitude greater than those in normal early type galaxies and similar to those in powerful radio galaxies.

From the Hα luminosity and the physical radius of each region we estimated the *rms* density and the mass of the very extended emission-line gas for the sources in our sample (see Table 1 for a representative set of sources). By assuming case B of recombination, the density in the emitting gas is given by

$$n_e^2(rms) = \frac{L_{H\alpha}}{V\ \alpha_{H\alpha}^{eff}\ h\ \nu_{H\alpha}}, \tag{1}$$

where $L_{H\alpha}$ is the Hα luminosity and V is the volume occupied by the emitting gas. We assumed an effective recombination coefficient $\alpha_{H\alpha}^{eff} = 1.17 \times 10^{-13}$ cm^3 s^{-1} (Osterbrock 1989).

The mass of the emission-line gas was estimated by assuming case B of recombination, from the relation,

$$M_{gas}(rms) = V\ n_e(rms)\ m_p = \frac{L_{H\alpha}\ m_p}{\alpha_{H\alpha}^{eff}\ h\ \nu_{H\alpha}\ n_e}. \tag{2}$$

The values for $n_e(rms)$ and mass are listed in Table 1, for a subset of the sources in our sample. These values range from ~ 0.01 to 0.26 cm^{-3} for n_e, and between 1.16×10^8 to 2.63×10^9 $M_\odot$ for M_{gas}.

TABLE 1
PHYSICAL CONDITIONS IN THE EXTENDED EMISSION-LINE GAS

Source B2	$L_{H\alpha}$ (10^{39} erg s^{-1})	n_e(rms) (cm^{-3})	M_{gas}(rms) (10^8 $M_\odot$)
0120+33	75.39	0.13	13.39
0331+39	5.67	0.01	1.16
0913+38	6.07	0.04	3.80
1339+26	26.70	0.08	7.97
1346+26	136.30	0.18	18.00
1422+26	10.03	0.05	4.88
1658+30	47.96	0.11	10.68
1855+37	1.15	0.02	1.65
2320+32	34.31	0.09	9.03

For both weak and strong radio galaxies, we find a strong correlation of the radio luminosity and the core radio-power with the optical emission-line luminosity, which are presented in Figure 2. We show that intense radio-luminosity sources have intense line-luminosities and large core radio-power. Figure 2 (*left*) shows that WRGs are located near the region of Seyfert galaxies (which are also radio weak), strongly suggesting a common origin to the continuum and line emission. Besides, WRGs appear weaker in radio- and line-luminosity than powerful radio galaxies or quasars but all the sources follow a similar correlation. These correlations seem to point to a common energy source for both the optical line- and radio-emission. If the radio luminosity of a galaxy is determined, to first order, by the properties of its central engine, our results suggest that the optical emission-line gas is also powered by the nuclear continuum.

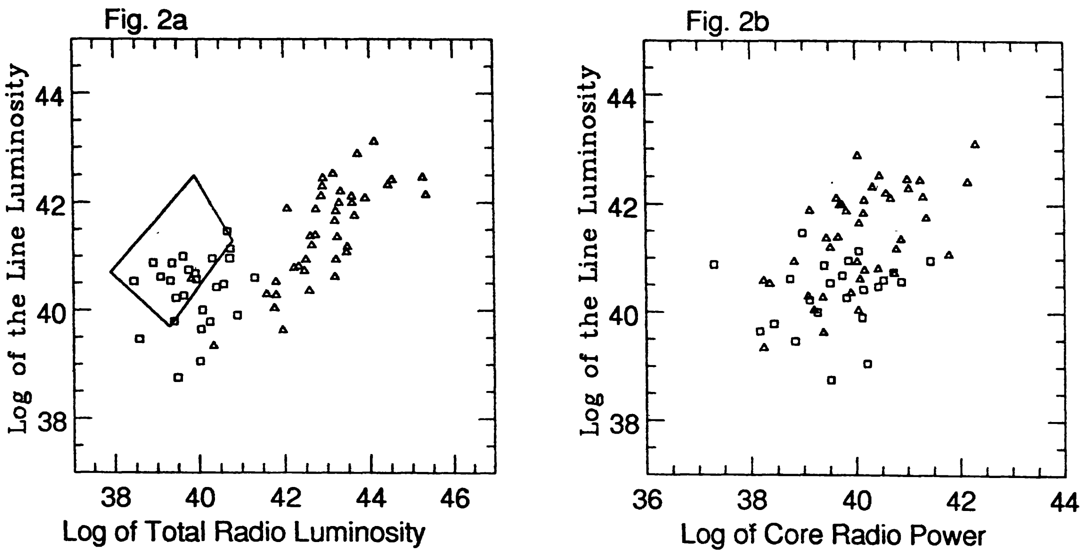

Fig. 2. Correlation of the radio-luminosity (*Left*) and core radio-power (*Right*) with the optical emission-line luminosity. □ WRGs from our sample, ◇ Whittle (1985) and de Bruy & Wilson (1978), △ Baum & Heckman (1989). The region of Seyfert galaxies is marked in the left figure.

5. CONCLUSIONS

This work summarizes the results of a study of the optical properties and the emitting-line gas of a representative sample of weak radio galaxies. Our main results are:

a) Spatially extended emission-line gas is quite common in weak radio galaxies. Line emission is detected in all the sources in the sample and 81% of them have resolved emission-line nebulae.

b) The mean size of the emission-line nebulae is ~ 4.6 kpc, and the mean emission-line luminosity in $H\alpha +$ [N II] or [O III] is $\sim 1.1 \times 10^{41}$ erg s^{-1}. The latter is one order of magnitude greater than the luminosity of emission-line nebulae in normal early-type galaxies, and similar to that of powerful radio galaxies.

c) The emission-line nebulae have a wide range of sizes and morphologies. In some sources we observe only small, centrally condensed, kpc scale regions, while in others we detect much more extended filaments several kiloparsecs from the host galaxy nucleus.

d) We find strong correlations of the emission-line luminosity with both the total radio-luminosity and the core radio-power. WRGs were shown to be fainter, in radio-luminosity and line-luminosity, than powerful radio galaxies or quasars but all sources follow a similar correlation. WRGs are located near the region of Seyfert galaxies strongly suggesting a common origin to continuum and line emission for both types of AGNs.

e) We estimate the *rms* density and the total mass of the emission-line gas to be in the ranges ~ 0.01 to 0.26 cm^{-3} and 1.16×10^8 to 2.63×10^9 $M_\odot$, respectively.

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to put a large fraction of their total massive star formation into a single giant H II region (Hunter & Gallagher 1985).

There are actually two parameters in the "scale" of a star-forming region that I would like to consider. There is the total number of stars in a given mass or luminosity range that have formed in a particular event and there is the density of the stars, the amount by which those stars are concentrated in space. The hundreds of massive stars in giant H II regions, for example, may be concentrated in compact clusters or they may be more spread out, as in OB associations or open clusters.

Our understanding of star formation can profit by such a diversity of star-forming regions which serve as unique clues to the star formation process. An interesting question is whether the star formation process in any way differs with the size of the region: Are 10 small regions equivalent to one region that is 10 times bigger? Furthermore, what are the galactic conditions necessary to form stellar groups of different sizes and/or concentrations? The question of sizes is really a question of what conditions are necessary to form gas clouds of different sizes since it seems likely that larger clouds are necessary to form larger star-forming units. But, the question of concentrations of stars may be related to more than just the size of the cloud. In this paper I would like to illustrate the range in scales of star-forming units and summarize some of what is known about the star-formation process, particularly from the stellar products.

2. NORMAL ASSOCIATIONS AND CLUSTERS

When one thinks about star-forming regions, one usually pictures OB associations or open clusters. These units are the most common of what is readily visible in other galaxies. They contain some tens to hundreds of massive stars in relatively loose groups, and, therefore represent a modest concentration of young stars. Table 1 lists some concentrations of luminous stars for a variety of objects, including the study by Massey, Johnson, & Degioia-Eastwood (1995b) of a dozen OB associations in the Milky Way and the LMC. (Massey et al. counted stars with masses $> 10\ M_\odot$ whereas the other entries in Table 1 count stars with $M_V < -4$). Massey et al. found a density of 0.02 stars pc^{-2} for stars $>10\ M_\odot$ with a factor of two variation from this for all but one association. Interestingly, this density is much higher than that in the giant OB association NGC 206 in M31 which has a density of massive stars of only 0.0007 stars pc^{-2} for the half of the association surveyed by Hunter et al. (1995c). Even the giant H II region NGC 604 in M33 has a massive star density of only 0.02 stars pc^{-2} (Hunter et al. 1995b). Thus, a larger number of massive stars does not necessarily imply a higher concentration of those stars.

TABLE 1

SOME STELLAR DENSITIES

Object	N_*	Density (stars pc^{-2})	Reference
R136	122	1.8	Hunter et al. 1995a
30 Doradus	450	0.05	Parker & Garmany 1993 Hunter et al. 1995a
Milky Way–OB	6–82	0.02	Massey et al. 1995b
LMC–OB	40–84	0.02	Massey et al. 1995b
I Zw18–shell	225	0.02	Hunter & Thronson 1995
I Zw18–south	79	0.004	Hunter & Thronson 1995
NGC 604	186	0.02	Hunter et al. 1995b
NGC 206	187	0.0007	Hunter et al. 1995c

Although we do not understand the physics behind the stellar initial mass function (IMF), people use that as an observational diagnostic of the star formation process. The assumption is that if the IMF is the same in different regions, then the star formation process was the same too. Numerous OB associations in our Galaxy and the Magellanic Clouds have been tediously examined star-by-star in order to determine the IMF of the stars that have formed. Table 2 lists the results of some of these studies. With one exception, the IMFs for massive and intermediate mass stars appear to be near that of a Salpeter's IMF (Salpeter 1955; slope$\sim$−1.35). Since the galaxies cover a factor of about 8 in oxygen abundance and the associations are found at varying distances