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PHOTOIONIZATION AND SHOCK MODELLING OF THE H II REGION ABUNDANCE SEQUENCE AND OF LUMINOUS INFRARED GALAXIES

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RESUMEN

Recalibramos la secuencia de abundancias de regiones H II extragalácticas y comparamos modelos de fotoionización y de choques para una muestra luminosa de galaxias australes con brotes de formación estelar. Encontramos que las regiones H II son jóvenes. Las galaxias IR luminosas son excitadas por la formación contínua de estrellas o por AGNs y tienen metalicidades mayores a la solar.

ABSTRACT

We recalibrate the abundance sequence for extragalactic H II regions and compare photoionization and shock models for a luminous sub-sample of southern starburst galaxies. We find H II regions are young. Luminous IR galaxies are excited by continuous star formation and/or AGN and have higher than solar metallicity.

Key Words: **GALAXIES: ABUNDANCES — GALAXIES: ISM — GALAXIES: STARBURST — H II REGIONS**

1. INTRODUCTION & DATA SETS

Observations of giant extragalactic H II regions have revealed the abundance gradients in external galaxies. The systematic change in emission line ratios with abundance was first clearly revealed by McCall, Rybski, & Shields (1985), and H II regions occupy narrow well-defined zones on line diagnostic plots e.g., Veilleux & Osterbrock (1987), Osterbrock, Tran, & Veilleux (1992). This abundance sequence was first calibrated semiempirically by authors such as Pagel et al. (1979) and Alloin et al. (1979), and theoretically by Dopita & Evans (1986) and McGaugh (1991). Starburst galaxies have very similar line ratios to H II regions, but are shifted systematically with respect to them. Recent advances in nebular physics enable better modelling. In particular, we can now generate self-consistent ionizing UV radiation fields as a function of cluster age, and we can self-consistently treat dust physics and depletion, thanks to the rapid progress that has been achieved with space telescopes such as *ISO* and the *Hubble Space Telescope*. Here, we confront observations with self-consistent models to discover what we can learn about the re-calibration of the extragalactic H II region abundance sequence, and to find what makes the starburst galaxies different from H II regions.

We have selected four recent homogenous and extensive H II region data sets: Kennicutt & Garnett (1996), Roy & Walsh (1997), Walsh & Roy (1997) and van Zee et al. (1998). We have also selected 285 luminous infrared galaxies from the Strauss et al. (1992) catalogue with "warm" IR colours—more likely to be associated with AGN. From these, we analyzed a luminous sub-sample of 61 galaxies with the following statistical properties: Galactic latitude $|b| > 15$, declination $\delta < +10$, redshift $z < 0.025$, luminosity, $\log[L_{\rm FIR}/L_{\odot}] > 9.5$, $F_{60\mu m} > 6$ Jy and $F_{60\mu m}/F_{25\mu m} < 8$. All have good S/N data in all *IRAS* wavebands. We used the 2.3-m telescope at Siding Spring Observatory to obtain high resolution ($\Delta v \leq 40$ km s^{-1}) spectroscopy in both the Hα and Hβ spectral regions. In addition, all galaxies have been seached for compact radio sources using the Parkes-Tidbinbilla Interferometer (PTI)—sensitive to unresolved sources with brightness temperatures $> 10^5$ K. Most

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of these galaxies are dominated by starbursts. However, eight out of the ten most radio luminous objects have Seyfert-like line ratios and properties, and are clearly AGN. Curiously enough, a large fraction of the starburst-dominated also contain compact radio sources. However, these are at least a factor of ten fainter than the AGN, and may be compact radio supernova remnants with a diameter < 2 pc (Kewley et al. 2000). The remaining objects are composite in nature with line ratios intermediate between starbursts and the AGN.

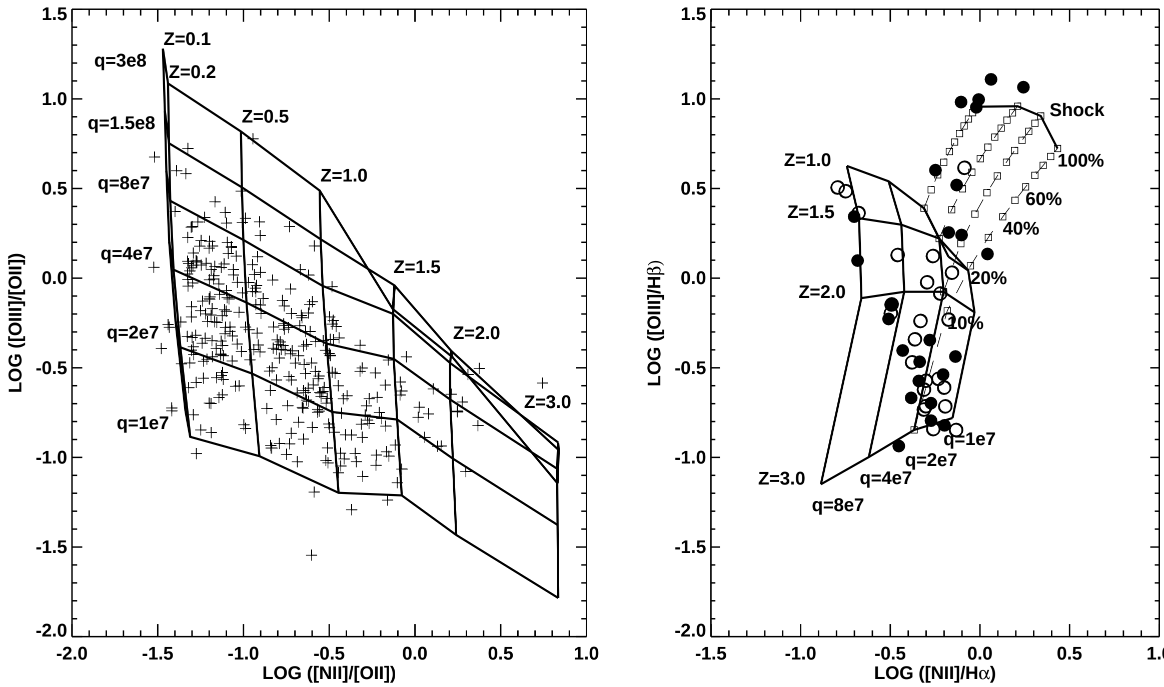

Fig. 1. *(a)* (Left) This H II region diagnostic diagram separates ionization parameter and metallicity. The grid is for instantaneous star formation. *(b)* (Right) Grids for continuous star formation, and for fast shocks are shown along with mixing lines of constant metallicity and data on IR galaxies. The filled circles distinguish objects with compact radio sources. All galaxies have metallicities greater than solar.

2. MODELS

To model the evolution of the cluster UV radiation as a function of time, we have used the PEGASE code (Fioc & Rocca-Volmerange, 1997). The cluster IMF was assumed to be of the Salpeter form, with an upper mass cutoff of 120 $M_\odot$. The star formation rate was taken to be constant from some initial time. Due to the rapid evolution of the high-mass stars, the shape of the UV spectrum evolves rapidly during the first ~ 3 Myr, but then achieves a shape which is independent of time until much later times. This time dependence of the UV radiation field is reflected in the emission line ratios, and provides a discriminant between the "continuous" and "instantaneous" star formation limits.

To model the H II region spectrum as a function of age of the exciting stars, metallicity and ionization parameter, we input the ionizing spectrum from the PEGASE models into the MAPPINGS v3.0 code described in Sutherland & Dopita (1993). This code has evolved and diverged from the version of the code currently used by Binette (e.g., this conference). We use plane parallel, isobaric models (with $P/k = 10^5$) to avoid spherical divergence effects on the mean ionization parameter q, the ratio of photons passing through a unit area to the number density of H atoms, or equivalently the maximum velocity of the ionization front that can be driven by the radiation field. Dust physics is treated explicitly through its absorption of the radiation field and photoelectric heating. The dust model consists of silicate grains and small organic grains, and is chosen so as to give the observed depletion factors, and the observed absorption per hydrogen atom for solar metallicity. All elements except nitrogen and helium are taken to be primary. Nitrogen is assumed to be a secondary element above metallicities of 1/10 solar, and helium is taken to have a primary component in addition to its primordial value. The AGN are modelled as 500 km s^{-1} radiative shocks with photoionized precursors (Dopita & Sutherland 1995). We assume dust is destroyed in the shock, but survives unaltered in the precursor.

3. RESULTS

We find that the extragalactic H II region sequence is reproduced remarkably well by our models, provided that the clusters which excite them are all rather young (< 2 Myr). This is a selection effect—young high surface brightness regions are preferentially observed. We find that the line ratio usually used for measuring the ionization parameter; [O III] 5007 Å/ [O II] 3726,9 Å , is indeed a good diagnostic. Amongst other easily observed line ratios we found that the [N II] 6584 Å/ [O II] 3726,9 Å ratio gives the best diagnostic of abundance, as it is monatonic between 0.1 and over 3.0 times solar metallicity (see Fig. 1*a*). This is because nitrogen is a secondary element and its relative abundance increases at high metallicity, and also because high metallicity H II regions are cool, so that the [O II] 3726,9 Å lines are quenched. For the H II regions, we find abundances 0.1 – 2.5 solar, and ionization parameters in the range $10^7 < q < 10^8$ (or $U \equiv q/c$ in the range $-3.5 < \log U < -2.5$).

The luminous starburst galaxies in our sample are best explained as H II regions excited by stars of a wide variety of ages, in a region of continuous star formation. The ionization parameters seem to be somewhat lower than those found in giant extragalactic H II regions. In addition, *all* of these objects appear to have metallicities in excess of solar, and values as high as three times solar are inferred for some objects. The galaxies showing "pure" Seyfert line ratios can also be explained as radiative fast shocks propagating in a greater than solar metallicity gas. Objects with intermediate line ratios appear to be composite in character, and lie on mixing lines between the fast shock and phototoionized H II regions of the same metallicity (see Fig. 1*b*).

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