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The dynamics and chemical composition of giant extragalactic H II regions

Roberto Terlevich *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*

Jorge Melnick *European Southern Observatory, Geneva, Switzerland*

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Summary. We analyse the correlations between Hβ luminosities, linear diameters and the widths of the global emission-line profiles of giant extragalactic H II regions and detached extragalactic H II regions. After correction for luminosity evolution, giant H II regions satisfy the same luminosity–velocity dispersion relation followed by elliptical galaxies, bulges of spiral galaxies and globular clusters. We also show that the correlation between size and line width is similar to the one valid for elliptical galaxies and globular clusters. These results strongly suggest that giant H II regions are self-gravitating systems, where the emission-line profile widths reflect the motions in the local gravitational field.

The scatter observed in the Hβ luminosity–linewidth relation is found to be largely due to a metallicity effect. This implies that giant H II regions and detached extragalactic H II regions are at least a two-parameter family. After correction for this effect, the scatter in the corrected relation is less than 0.5 mag, consistent with the observational errors. The importance of these results as a new method for distance calibration and for the study of star formation and evolution in extragalactic systems is emphasized.

1 Introduction

The giant H II regions in M33, M101 and 30 Doradus in the Large Magellanic Cloud (LMC) are the largest and brightest H II regions observable; they are outstanding objects quite different from the other H II regions in these galaxies. Giant H II regions are ionized by massive star clusters while only a few OB stars are required to ionize normal nebulae. Smith & Weedman (1970) have found that the overall emission-line profile widths of giant H II regions imply the existence of highly supersonic motions in these nebulae. By contrast, the width of emission lines in 'normal' H II regions in our Galaxy seldom exceed the sound speed in the ionized gas. Since supersonic motions cannot be generated by radiation from the exciting stars, the kinematical properties of giant H II regions must differ radically from those of normal nebulae.

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Sargent & Searle (1970) have identified a class of blue compact galaxies having spectroscopic properties similar to those of giant extragalactic H II regions; the overall luminosities of these systems are dominated by the H II region-like component. Sargent & Searle have therefore called these objects 'isolated' extragalactic H II regions.

In this paper we reanalyse the relations between Hβ luminosity, linewidth, metallicity and size, of both 'arm' and isolated or 'detached' giant extragalactic H II regions. We show that the relations

luminosity $\propto$ (linewidth)^4

and

size $\propto$ (linewidth)^2

which are valid for pressure-supported stellar systems (elliptical galaxies, bulges of spiral galaxies and globular clusters) are also valid for giant H II regions. From this and other considerations we conclude that giant extragalactic H II regions are self-gravitating systems in which the observed emission-line profile widths represent the velocity dispersion of discrete gas clouds in the gravitational potential of the gas–star complex.

We also show that the scatter in the luminosity–velocity dispersion relation is correlated with metal content in the sense that objects with high luminosity for their velocity dispersion show low metal abundance and objects with low luminosity for their velocity dispersion show high metallicity. This implies that the scatter is real, and suggests the existence of a second parameter which, together with the total luminosity, plays a fundamental role in determining the properties of extragalactic H II regions. After correcting for this effect, the remaining scatter is consistent with the observational errors. Velocity dispersions and metallicities, therefore, are good indicators of absolute luminosity for giant H II regions, and this provides a new method for mapping the Hubble flow. Using modern instruments, it should be possible to detect and observe spectroscopically giant H II regions out to distances of more than 1000 Mpc. Clearly these observations would also provide valuable information on star formation processes for a wide range of galaxy types and, therefore, increase our understanding of formation and evolution of galaxies.

2 Basic correlations

In this section we analyse the interrelations between giant H II region diameters, emission-line profile widths and Hβ luminosities for a sample of giant H II regions with core–halo morphology and medium to high-excitation spectra. Although restricting the sample in that way may introduce non-trivial selection effects, this is the only sample of extragalactic H II regions for which a significant body of data has been published.

2.1 RELATION BETWEEN RADIUS AND EMISSION-LINE PROFILE WIDTH

Melnick (1977) showed that the mean core–halo diameters $\langle D_C, D_H \rangle = \frac{1}{2}(D_C + D_H)$ of the largest H II regions in a subsample of the galaxies used by Sandage & Tammann (1974a; ST) in their calibration of the extragalactic distance scale, correlate with the width of the emission-line profiles as $\langle D_C, D_H \rangle \propto \sigma^{2.27}$ with $\sigma = 0.42$ FWHM. In the present study we prefer to use Sandage & Tammann's core radii $R_c = 0.5 D_c$, partly because most of the Hβ luminosity and all the ionizing stars belong to the nebular cores and partly because we believe that the ST diameters $\langle D_C, D_H \rangle$ actually overestimate the physical sizes of the H II regions.

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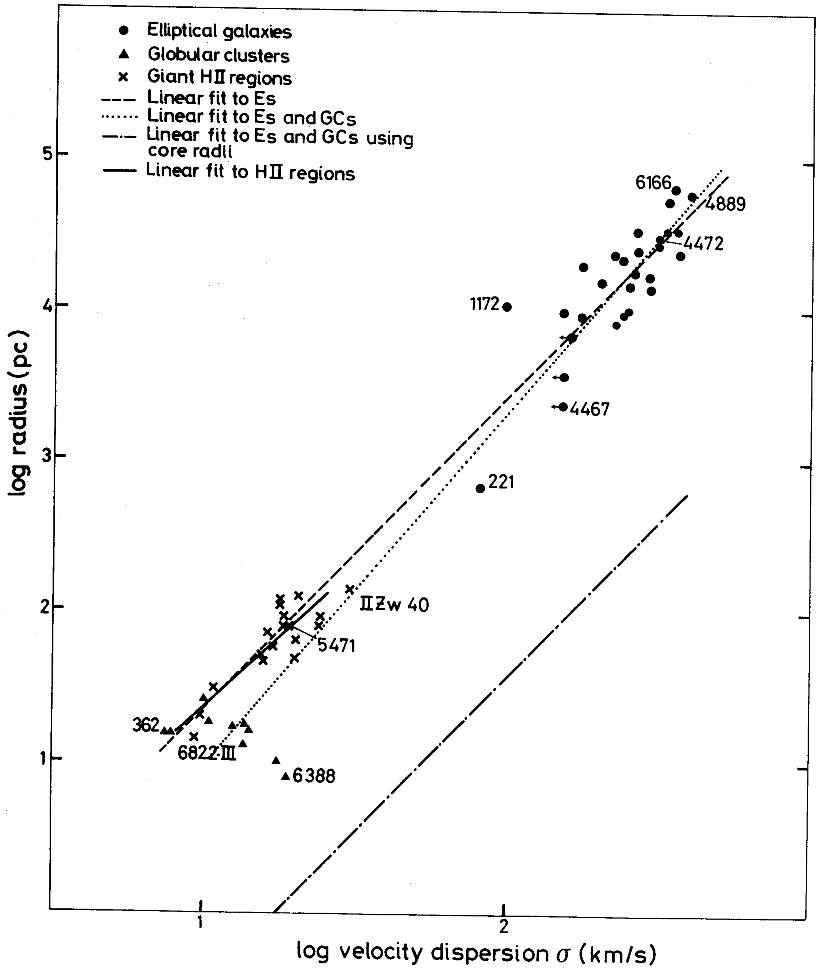

Figure 1. Correlation between radius and velocity dispersion for globular clusters, elliptical galaxies and giant extragalactic H II regions. The isophotal radii R_{25} of the Second Reference Catalogue have been used for elliptical galaxies while globular clusters are represented by their 90 per cent of the light radius R_{90}. The core radii R_c as defined in the text have been used for giant H II regions. The various lines represent power law fits to the data. When core radii are used instead of isophotal radii the correlation for GCs and Es conserves the same slope $R \propto \sigma^2$ as shown in the figure.

Fig. 1 shows a plot of R_c as a function of σ*. Included in that plot are both 'arm' H II regions and 'isolated' H II regions. The solid line through the data points represents a linear regression of the form,

$$\log R_c = 1.84 \log \sigma - 0.47 \tag{1}$$

derived using only the nebulae with Hβ photometry.

It is a well known observational fact (van den Bergh 1976) that there is a close correlation between the diameters and the luminosities of elliptical galaxies. Since, for these galaxies, $L \propto \sigma^4$, (Faber & Jackson 1976, see also Section 2.2) a relation between diameter and velocity dispersion must also exist for ellipticals. This is shown in Fig. 1 where the isophotal diameters R_{25} from the Second Reference Catalogue (de Vaucouleurs, de Vaucouleurs & Corwin 1976) have been plotted against velocity dispersions. Also plotted are globular clusters represented by the 90 per cent of the light radius, R_{90} as determined by Kron & Mayall (1960). This

* Throughout this work we assume a Hubble constant of 50 km s^{-1} Mpc^{-1}; sizes are given in pc, velocities in km s^{-1}, and fluxes in erg s^{-1}.

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inclusion is valid since, for either King or de Vaucouleurs ($r^{1/4}$) model, R_{90} is only a few per cent larger than R_{25}. The regression lines through the data have slopes $R \propto \sigma^{2.0}$ if only the ellipticals are considered and $R \propto \sigma^{2.4}$ if we use ellipticals and globular clusters. Also plotted in Fig. 1 is the regression line $R = 3.7 \times 10^{-3} \sigma^{2.0}$ obtained when the core radii of King (1978) for ellipticals and Illingworth (1976) for globular clusters are used instead of the isophotal radii.

The steeper slope found using photometric radii relative to the relation defined by the core radii is most likely due to tidal effects limiting the photometric radius of globular clusters. We conclude, therefore, that giant H II regions and pressure-supported stellar systems satisfy a similar relation between size and linewidth of the form $R \propto \sigma^2$. For giant H II regions alone the relation has the form

$$R_c = 0.21\,\sigma^2. \qquad (2)$$

2.2 RELATION BETWEEN Hβ LUMINOSITY AND LINE PROFILE WIDTHS

Melnick (1979a) found a correlation between the Hβ luminosity and profile width for giant H II regions. It was emphasized in that paper that the internal reddening corrections to the

Table 1. Observed parameters of giant extragalactic H II regions.

	V	$B-V$	R_c (pc)	σ (km s^{-1})	$\log F$(Hβ) (erg s^{-1})	C^{ext}(Hβ)	$M_T/10^6 M_\odot$	Z	Sources
NGC 604			112	17.8	38.75	0.05	7.8	0.0126	1,2,3,4,5
595			91	18.5	38.16	0.05	6.9		1,2,3
588				13.7	37.81	0.05		0.011	1,2,3,4
IC 131				15.5	37.65	0.05			1,2,3
NGC 2403–I			88	18.0	39.19	0.10	6.3		1,3,4,6
II			49	19.8	39.18	0.10	4.2		1,3,4,6
III			51	15.6	39.31	0.10	2.7		1,3,4,6
IV			47	15.3	38.99	0.10	2.4		1,3,4,6
NGC 2366–I			70	16.3	39.38	0.08	4.1	0.0026	1,3,6,14
4236–I			57	16.8	38.61	0.01	3.5		1,3,6
6822–I			20	9.8	37.57	0.43	0.42	0.0069	1,3,4,6
III			14	9.3	37.61	0.43	0.27	0.0058	1,3,4,6
NGC 5471	13.76	0.32	82	19.3	39.59	0.00	6.7	0.0033	1,2,3,4,6,7
5462	13.95	0.06	63	20.0	39.19	0.00	5.5		1,2,3,4,7
5455	15.05	0.11	96	23.9	39.29	0.00	12	0.0132	1,2,3,4,7
5461			80	19.0	39.67	0.00	6.4		1,2,3,4
5447			80	24.2		0.00	10	0.0120	1,2,4
SMC–I			30	10.7	(38.2)	0.03	0.76	0.0030	1,8,9,10,14
LMC–I			115	17.7	39.16	0.13	7.9	0.0072	1,11,12
IIZw40	15.6	0.69	165	31	40.0	1.00	35	0.0041	13,15,18
Tol924				30	41.2	0.05		0.0030	16,17,18
NGC 5253	11.43	0.29	90	21.1	39.9	0.05	8.8	0.0043	18,19
IIZw70				<25	39.9	0.03		0.0038	20,21

1. Sandage & Tammann (1974a). 2. Smith & Weedmann (1970). 3. Melnick (1979b). 4. Smith (1975a). 5. Peimbert & Spinrad (1970). 6. Melnick (1977). 7. Sandage & Tammann (1974b). 8. Melnick (1979a). 9. Pagel *et al.* (1978). 10. Dufour (1974). 11. Faulkner (1967). 12. Peimbert & Torres-Peimbert (1974). 13. Sargent & Searle (1970). 14. Kennicutt, Balick & Heckman (1981). 15. Baldwin & Carswell (private communication). 16. Ward (private communication). 17. Smith (1975b). 18. Terlevich (1980). 19. Osmer, Smith & Weedman (1974). 20. Lequeux *et al.* (1979). 21. O'Connell & Kraft (1972).

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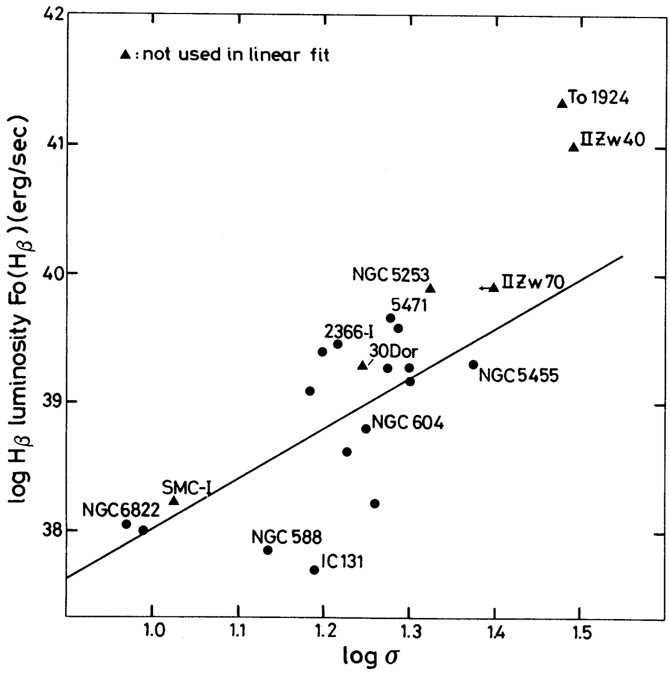

Figure 2. Logarithmic plot of the observed Hβ luminosities of giant extragalactic H II regions, corrected for galactic extinction, F_0 (Hβ), as a function of the rms widths of the emission line-profile σ. Included in the plot are both 'isolated' H II regions and 'arm' nebulae. The solid line represents a linear least square fit to the objects with Hβ photometry.

Hβ fluxes are extremely uncertain; not only do the absorption values determined by comparing radio continuum with Hβ fluxes differ from those calculated from the observed Balmer decrements, but the Balmer decrements themselves vary widely from place to place in the nebulae. Consequently, we have corrected the observed Hβ fluxes only for foreground galactic absorption. Table 1 gives the observed Hβ fluxes, F(Hβ), together with the adopted external (galactic) reddening corrections $C^{\rm ext}$ (Hβ) = $0.4 A_{\rm B}$, where $A_{\rm B} = 0.132\,(\operatorname{cosec} b - 1)$ (ST).

Fig. 2 shows a plot of the partially reddening corrected Hβ luminosities, $\log F_0$ (Hβ) = $\log F$(Hβ) + $C^{\rm ext}$(Hβ), as a function of Hα line-profile width (σ) for the H II regions in Melnick's sample, giant H II regions in some Zwicky and Tololo galaxies, and the nuclear region of NGC 5253. Also plotted on that figure is a least squares fit of the form,

$$\log F_0\,(\mathrm{H}\beta) = 4.0 \log \sigma + 34.0 \tag{3}$$

for those H II regions for which Melnick (1979a) gives integrated Hβ fluxes. This regression is not significantly different from the relation $\log I(\mathrm{H}\beta) = (4.2 \pm 1.2) \log \sigma + (33.5 \pm 1.6)$* obtained by Melnick using Hβ luminosities corrected for internal *and* external reddening. We conclude from this that the internal reddening corrections do not introduce systematic effects to the (F_0(Hβ) – σ) relation as defined by equation (3).

A relation with similar slope has also been found for elliptical galaxies (Faber & Jackson 1976) and bulges of spiral galaxies (Whitmore, Kirshner & Schechter 1979). In Fig. 3 we plotted the luminosity–velocity dispersion relation for ellipticals using data from Terlevich *et al.* (1981) for 24 ellipticals, from Whitmore *et al.* for the bulges of 17 spiral galaxies, and 10 globular clusters from Illingworth (1976). The regression line through the ellipticals, spiral bulges and globular clusters has the form

$$\log \sigma = -0.097\, M(B)_0 + 0.29, \tag{4}$$

similar to the result obtained by Terlevich *et al.* for the elliptical galaxies alone.

* The original correlation was expressed in terms of $V_{\rm turb} = \sqrt{2}\,\sigma$.

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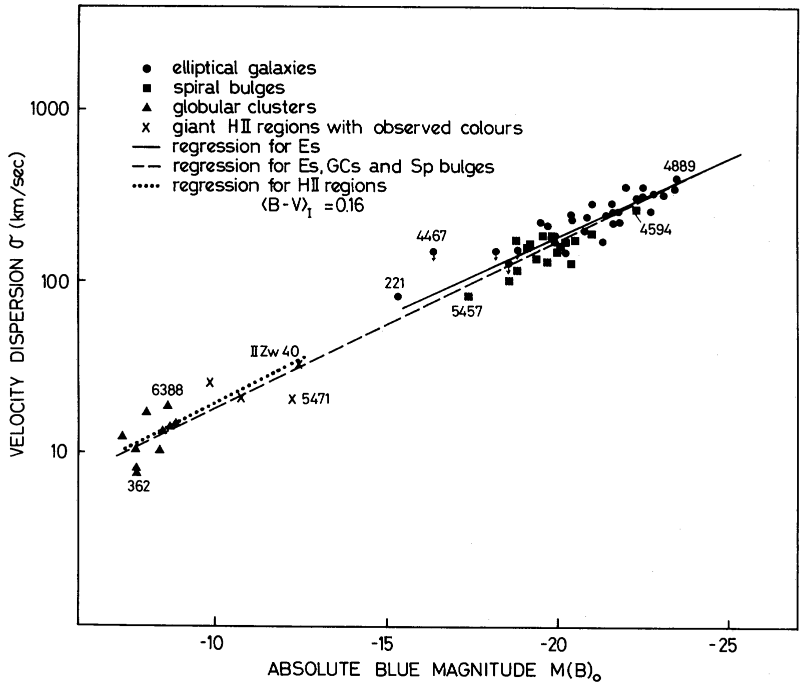

Figure 3. Correlation between absolute blue magnitude $M(B)_0$ and velocity dispersion for elliptical galaxies, bulges of spiral galaxies and globular clusters. The dashed line represents a linear fit to all the data. The solid line corresponds to a least squares fit to the elliptical galaxies alone. The dotted line represents the mean (F_0 (Hβ), σ) correlation line of Fig. 2 expressed in terms of the absolute blue magnitude of the ionizing star cluster corrected for evolution as described in the text. Individual H II regions with direct *UBV* photometry are also plotted.

It is straightforward to verify that systems satisfying relations of the form $L \propto \sigma^4$ and $R \propto \sigma^2$ must have constant surface brightnesses and M/L ratios (Sargent *et al.* 1977). We have shown that globular clusters, elliptical galaxies and spiral bulges define narrow (L, σ) and (R, σ) relations. This implies that these systems must have similar surface brightness and M/L ratios. In fact for globular clusters $1 \lesssim M/L \lesssim 3$ (Illingworth 1976) while for elliptical galaxies the M/L ratios lie in the range 4 to 10 (Faber & Jackson 1976; Schechter & Gunn 1979), on the average only a factor of 3 larger than globular clusters over a range of 10^8 in mass. Similarly, the average mean surface brightness of globular clusters is less than 1 mag brighter than the corresponding value for elliptical galaxies over a range of nearly 14 mag in luminosity.

3 The origin of the observed motions

It was shown in the previous section that the emission-line profile widths of giant H II regions exhibit the same dependence on luminosity ($L \propto \sigma^4$) as that found in systems where the velocities are purely gravitational. This suggests a similar origin for the observed motions in giant H II region cores. A direct check on this hypothesis is to compare the rms velocities implied by the nebular linewidths with the observed velocity dispersions of the stars in the ionizing clusters. In practice this is a very difficult observational test; the brightest stars in these clusters are early-type supergiants with few (if any) extremely broad absorption lines from which accurate radial velocities cannot be determined.

An alternative approach is to use the integrated luminosities of the clusters to obtain their

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velocity dispersions via the (L, σ) relation for self-gravitating systems (equation 4) and to compare these with the emission-line profile widths. The (L, σ) relation described by equation (4), however, is only valid for systems having similar M/L ratios while, clearly, the M/L ratios of H II region cores are strongly influenced by young massive stars and, therefore, differ widely from M/L ratios of globular clusters and elliptical galaxies. Thus, in order to apply the (L, σ) relation to H II region clusters, we must impose the condition that giant H II regions evolve in luminosity as closed systems (i.e. at constant mass). We may then follow the evolution of the central clusters until their colours and M/L ratios become similar to the colours and M/L ratios of globular clusters and elliptical galaxies and introduce the corresponding luminosities in equation (4) to obtain the velocity dispersions.

We use in this analysis the evolutionary models for single bursts of star formation of Larson & Tinsley (1978). For the range in $(B-V)$ colours of relevance here, the change in absolute blue magnitude as a function of colour in these models can be approximated with sufficient accuracy as

$$\Delta M_{\mathrm{B}} = 6.1\, \Delta (B-V). \tag{5}$$

For the observed range of $(B-V)$ colours of H II region cores, the absolute blue magnitude of the continuum can be expressed in terms of the Hβ luminosities as (Terlevich 1981)

$$B_{\mathrm{C}} = -2.5 \log\, [F_0(\mathrm{H}\beta)/W_\lambda] + 79.4, \tag{6}$$

where W_λ is the equivalent width of the Hβ line in Ångstroms. In the range of temperatures and densities observed in giant H II regions, equation (6) can be considered to represent, to an accuracy of better than 20 per cent, the absolute blue magnitude of the embedded stars. Combining this equation with equation (5) gives an expression for their absolute blue luminosity corrected for evolution and internal reddening as

$$M_*(B)_0 = B_{\mathrm{c}} + \left(\frac{6.1}{R_{\mathrm{B}}} - 1\right) A_{\mathrm{B}}^{\mathrm{int}} + 6.1\, \{\langle B-V\rangle_{\mathrm{T}} - \langle B-V\rangle_{\mathrm{I}}\}\,, \tag{7}$$

where $\langle B-V\rangle_{\mathrm{I}}$ is the mean *observed* colour of H II region cores corrected for foreground extinction and $\langle B-V\rangle_{\mathrm{T}}$ is the mean colour of the cluster after all the massive stars have evolved off the main sequence. $A_{\mathrm{B}}^{\mathrm{int}}$ is the internal absorption in magnitudes and $R_{\mathrm{B}} = A_{\mathrm{B}}/E(B-V)$ the ratio of total to selective absorption for the dust grains *within* the H II regions. Sandage & Tammann (1974b) give integrated $(B-V)$ colours for three nebulae in M101. We adopt the unweighted average of these values as representative of the mean $(B-V)$ colour of the H II regions in our sample, $\langle B-V\rangle_{\mathrm{I}} = 0.16$. The final colour after evolution will be assumed to be equal to $\langle B-V\rangle_{\mathrm{T}} = 0.75$ corresponding to the mean observed colour of globular clusters.

The dependence of $M_*(B)_0$ on internal extinction rests on the value of R_{B} for the dust within giant extragalactic H II regions. The mean value for our galaxy is around $R_{\mathrm{B}} = 4.1$ (Turner 1976). It has been argued by Melnick (1979a), however, that the extinction law in several giant nebulae is significantly different from the mean law for OB stars in the galaxy, and resembles closely the observed reddening law of the visual light of the Trapezium stars in the Orion nebula, where Münch & Persson (1971) find $4 < R_{\mathrm{B}} < 6$. If R_{B} is in this range, $M_*(B)_0$ depends only very weakly on internal extinction.

In Fig. 3 we have plotted the mean $(F_0(\mathrm{H}\beta), \sigma)$ relation (equation 2) expressed in terms of $M_*(B)_0$ using a mean equivalent width $\langle W_\lambda\rangle = 145$ Å and neglecting the reddening term in equation (7). The adopted value for $\langle W_\lambda\rangle$ corresponds to the mean value of four nebulae in our sample for which Searle (1971) gives individual equivalent widths. It can be seen in

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Table 2. Comparison between 21-cm and Hα line profile widths.

H II region	Galaxy	$\sigma_{21\,\mathrm{cm}}$	$\sigma_{\mathrm{H}\alpha}$	Sources
Hubble X	NGC 6822	11	9.8	1
NGC 5447	M101	18	24.2	2
NGC 604	M33	17	17.8	3
30 Dor	LMC	19	17.7	4
IIZw40		29	31.0	5

1. Gottesman & Weliachew (1977). 2. Allen & Goss (1979). 3. Wright (1971). 4. McGee & Milton (1966). 5. Jaffe, Perola & Tarenghi (1978).

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that figure that within the uncertainties giant H II regions satisfy the *same* (L, σ) relation followed by globular clusters, elliptical galaxies and spiral bulges.

The fact that giant H II regions satisfy the same relations between size, luminosity and velocity dispersion followed by self-gravitating systems leads to the conclusion that giant H II regions are gravitationally bound complexes of stars and gas and that the widths of the nebular emission lines reflect motions of discrete ionized gas clouds in the gravitational field of the underlying stellar and gaseous mass. This conclusion is further strengthened by the coincidence between the turbulent widths of the Hα and 21-cm lines in these objects. Table 2 shows a comparison between Hα and 21-cm profile widths corrected for instrumental and thermal broadening for five H II regions with published high-resolution interferometric radio observations. With the possible exception of NGC 5447 for which $\sigma_{\mathrm{H}\alpha}/\sigma_{21} \sim 1.3$, the radio and optical dispersions are formally identical.

The virial theorem can be used to estimate the masses of giant H II regions from the observed velocity dispersions. Assuming that the mass distribution of these objects can be approximated as $M(r) = M_0/(1 + r^2/r_c^2)^{3/2}$ truncated at $r/r_c = 60$* the total mass within a radius $r = R_c$ is given by

$$\frac{M_T}{M_\odot} = 220\,(R_c)_{\mathrm{pc}}\,\sigma^2_{\mathrm{km\,s^{-1}}}. \tag{8}$$

Estimates of M_T using this formula are given in Table 1.

4 The scatter in the $(F_0(\mathrm{H}\beta), \sigma)$ relation

A close inspection of Fig. 2 and the metallicities of Table 1 shows that, for a similar velocity dispersion, H II regions above the regression line in Fig. 2 are systematically *metal poor* relative to the nebulae below the mean line. This remarkable result can be visualized better in Fig. 4 where the metallicity, Z, has been plotted as a function of $\Delta \log F(\mathrm{H}\beta) = 4 \log \sigma + 34.0 - \log F_0\,(\mathrm{H}\beta)$. The linear least squares fit to the data,

$$\Delta \log F(\mathrm{H}\beta) = 127z - 1.17 \tag{9}$$

has a scatter consistent with the observational errors.

An immediate consequence of this correlation is that most of the scatter in the $(F_0\,(\mathrm{H}\beta), \sigma)$ relation is real and is due to a metallicity effect and not to uncertainties in the internal reddening corrections as originally proposed by Melnick (1979b). Systematic changes of the optical depth of dust as a function of metallicity are unlikely since there is no correlation

* From the (R, σ) relations of Fig. 1 we obtain a mean ratio of 60 between isophotal and core radii.

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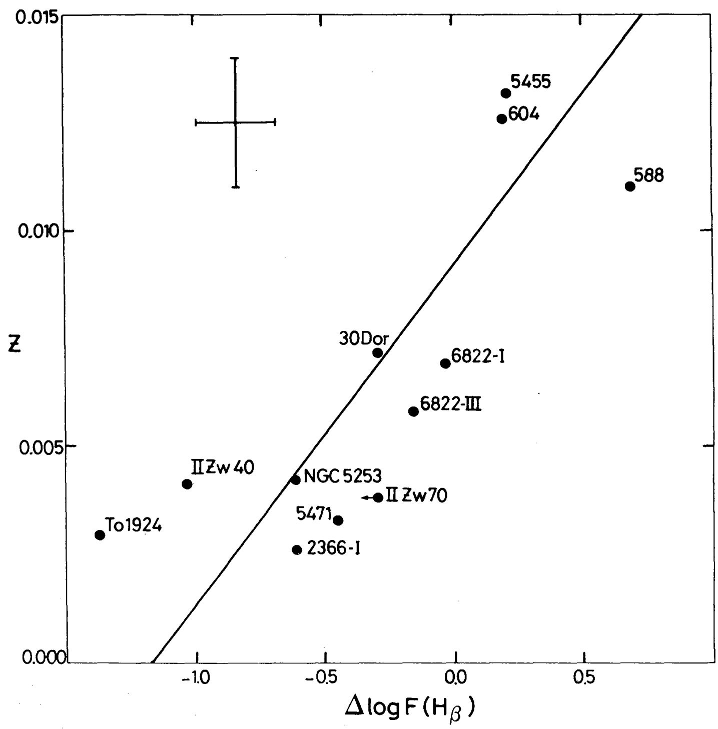

Figure 4. Plot between metallicity, Z, and Hβ luminosity excess, $\Delta \log F(\text{H}\beta)$, as defined in the text. Typical error bars are shown. The solid line represents a least squares fit to the data.

between metal content and internal absorption (as determined using either radio continuum to Hβ flux ratios or Balmer decrements) and since similar correlations to those of Fig. 2 (equation 3) and Fig. 4 (equation 9) are obtained using radio continuum observations instead of Hβ luminosities (Terlevich *et al.* 1981). If giant H II regions are ionization bounded, the correlation between $\Delta \log F(\text{H}\beta)$ and Z suggests that the ionizing flux per unit total mass of these objects changes systematically with metal content.

Using equation (9) it is possible to compute the systematic differences between H II regions with different metallicities and, therefore, to reduce the observed $F_0(\text{H}\beta)$ to some particular Z = constant line. For simplicity we choose $Z = 0$ for which $\Delta \log F(\text{H}\beta) = 127\,Z$ is the correction in luminosity. Fig. 5 shows a plot of the corrected Hβ luminosities $F_Z(\text{H}\beta)$ as a function of σ. The scatter has been greatly reduced and is $\sigma[\delta \log F_Z(\text{H}\beta)] = 0.20$ consistent with the observational errors. These results indicate that giant extragalactic H II regions form a far more homogeneous class of objects than had hitherto been realized, and may provide a powerful method of investigating the intrinsic characteristics of active regions of star formation, and of using these regions as probes of the large scale properties of the Universe.

5 The origin of the metallicity dependence

In view of the inhomogeneous origin of the data (regarding in particular metallicities and Hβ luminosities) and the possible selection effects involved, further high-quality data are required to confirm or deny the correlation between luminosity excess and metal content in giant H II regions. Nevertheless, we shall suggest some mechanisms which could lead to such a relationship.

The first explanation of this effect is based on the 'simple' model for chemical evolution of closed systems (for a review see Audouze & Tinsley 1976). Assuming the mass in young

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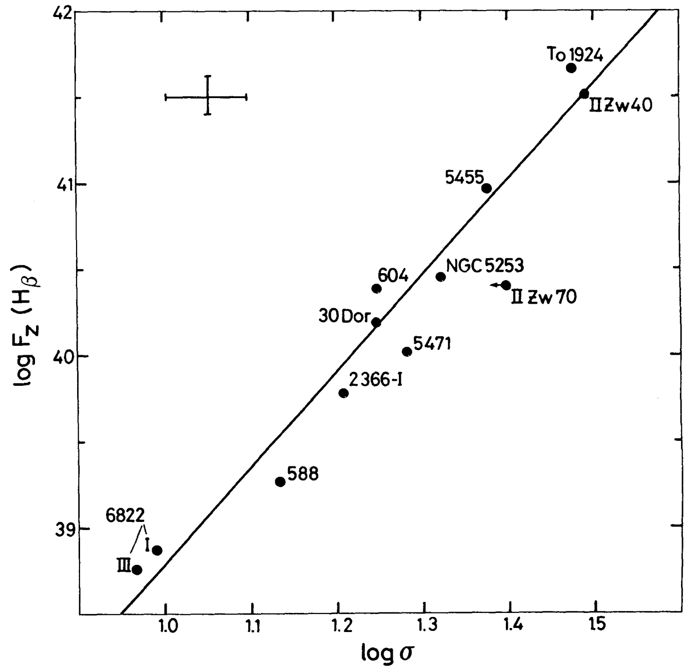

Figure 5. Correlation between corrected Hβ luminosity, F_Z(Hβ), and velocity dispersion. The scatter relative to the (F_0 (Hβ), σ) relation of Fig. 2 has been greatly reduced after normalization to a constant metallicity and is consistent with the observational errors. Typical error bars are shown.

stars of the current burst of star formation to be proportional to the mass of gas present *before* the burst, more metallic H II regions (i.e. those having undergone more cycles of star formation) will have lower Hβ luminosities per unit mass. Under this assumption the heavy element yield p is proportional to the reciprocal of the slope of the ($\Delta \log F$(Hβ), Z) relation (see Appendix)

$$p = \frac{1}{127 \ln 10} = 0.0034$$

in good agreement with the values obtained by Lequeux *et al.* (1979) ($p = 0.0038$) and Pagel *et al.* (1978) ($p = 0.003$) for similar objects using a completely different approach. This agreement, however, must be interpreted with caution; the basic hypothesis that giant H II regions evolve as closed systems over periods of time very long compared with the mean duration of a star formation burst and therefore much longer than dynamical time-scales is difficult to support since gas exchange (infall, outflow) with the surrounding medium will be expected in time-scales of the order of the crossing times in these objects.

An alternative way to explain the correlation between $\Delta \log [F(\text{H}\beta)]$ and Z is to assume that the initial mass function (IMF) depends on metallicity. This hypothesis was originally put forward by Schmidt (1963) to explain the G-dwarf problem in our galaxy and is further supported by recent observations of open clusters and OB associations (Burki 1979; Boissé *et al.* 1981). A dependence of the IMF on metal content has also been invoked by Shields & Tinsley (1976) to account for the radial gradient in the equivalent width of Hβ observed in H II regions of M101.

On the basis of evolutionary models of massive Population II and Population I stars, including the effects of mass loss (Melnick, Terlevich & Eggleton 1981) we estimate that a change of 0.6 in the slope of the IMF is required to explain the observed change in $\Delta \log [F(\text{H}\beta)]$ with metallicity (corresponding to a factor of 4 change in Z).

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6 Summary and conclusions

We summarize the main results from the present investigation.

1. Giant H II regions satisfy the same relations between size, luminosity, and velocity dispersion followed by gravitationally bound stellar systems, suggesting that giant H II regions themselves are gravitationally bound.

2. The observed emission-line profile widths represent the velocity dispersion of ionized gas clouds moving in the overall gravitational potential of gas and stars.

3. Giant extragalactic H II regions form at least a two-parameter family of objects. Their integrated luminosities are specified by their velocity dispersions and metallicities.

4. The ionizing flux per unit total mass of a burst of star formation seems to decrease with increasing metal abundance.

5. The metallicity-corrected relation $\mathscr{L}_\beta = \mathscr{L}_\beta(\sigma)$ has an rms scatter at fixed σ of about 0.5 mag consistent with the expected measurement errors.

The implications of these results for our understanding of formation and evolution of galaxies are far reaching. It is, therefore, of great importance to establish the correlations between luminosity, velocity dispersion and metallicity over a broader range of metallicities and luminosities. This, in turn, requires *accurate* observations of a larger sample of giant H II regions in a wide variety of environmental conditions.

A second important consequence of our results is that the correlation between Hβ luminosity, emission-line profile width and metallicity may provide a new method for distance determination. Using large telescopes and modern detectors these parameters can be *directly* determined for intergalactic H II regions out to distances of more than 1000 Mpc. The cosmological importance of mapping the Hubble flow out to large distances cannot be overemphasized. Also, these correlations can be calibrated using giant H II regions in nearby galaxies with known distances as a method to obtain accurate distances to field spiral and irregular galaxies well beyond the Virgo cluster.

Finally, we remark that our results are based on a very small sample of giant extragalactic H II regions. Further high-quality data are required to find definite answers to the questions raised by the present investigation.

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Appendix

It is possible to express the total luminosity in terms of σ and Z using equations (3) and (5) as,

$$\log F_0(\mathrm{H}\beta) = 4.0 \log \sigma - 127Z + 35.17$$

or

$$\log \frac{\sigma^4}{F_0(\mathrm{H}\beta)} = 127Z - 35.17. \tag{A1}$$

Since $R_c = 0.21\,\sigma^2$, the overall masses of giant H II regions can be expressed as a function of only the velocity dispersion as (equation 8)

$$\frac{M_\mathrm{T}}{M_\odot} = 46\,\sigma^4\,\mathrm{km\,s^{-1}}. \tag{A2}$$

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For our sample the ratio R_c/σ^2 is independent of metallicity; thus, the σ^4 term in equation (A2) can be replaced by M_T without changing the dependence on Z.

$F_0(\mathrm{H}\beta)$ can be related to the mass of young stars M_y (the total mass of stars formed in the current burst) as

$$F_0(\mathrm{H}\beta) = \phi M_y \, 10^{-0.4 A_B^{\mathrm{int}}}, \tag{A3}$$

where the parameter ϕ depends on the IMF of the young stars. The mass of young stars, in turn, is related to the mass of gas M_G, present before the initiation of the current burst of star formation by some coefficient measuring the efficiency of turning gas into stars

$$M_y = \eta M_G \tag{A4}$$

Introducing (A4), (A3) and (A2) into (A1) we find

$$\log \frac{M_T}{M_G} = 127 z + \log \phi + \log \eta - 0.4 A_B^{\mathrm{int}} + \text{constant}.$$

The 'simple' model of chemical evolution of a closed volume predicts,

$$\ln \left(\frac{M_T}{M_G}\right) = \frac{z}{p},$$

where p is the nucleosynthesis yield. Thus, if the parameters ϕ and η are independent of metallicity (A_B^{int} does not depend on Z),

$$p = \frac{1}{127 \ln 10}.$$

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