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Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
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DENSITY BOUNDING IN THE H II REGIONS OF GALACTIC DISKS: EVIDENCE AND CONSEQUENCES

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RESUMEN

Presentamos cuatro tipos de evidencia que conducen a la conclusión de que una fracción notable de los fotones ionizantes emitidos por las estrellas que se encuentran en el interior de las regiones H II en los discos de las galaxias espirales normales, escapa de las regiones hacia el medio circundante y más allá de éste. Éstas son: (1) La distribución de la intensidad de brillo superficial del Hα difuso emitido por el disco de una galaxia, es bien modelado suponiendo que el continuo de Lyman que lo origina escapa de las regiones H II. (2) La relación entre el brillo superficial central en Hα y la luminosidad total de una región H II, se aleja de las predicciones para sistemas uniformes limitados en ionización. (3) La función de luminosidad en Hα de poblaciones completas de regiones H II muestra un cambio de pendiente con parámetros que pueden explicarse con la hipótesis de limitación en densidad, pero no mediante hipótesis competidoras. (4) La relación entre anchura de velocidad interna en Hα y la luminosidad de las regiones H II se puede explicar de manera natural mediante la limitación en densidad. Una estructura de nube fractal y grumosa proporciona parámetros que pueden explicar las observaciones. Mostramos cómo la fracción de fotones Lyman que escapan de las regiones H II, finalmente escapa de los discos de las galaxias, y puede ionizar grandes volúmenes del medio de baja densidad interior a los cúmulos, en torno a las galaxias.

ABSTRACT

We present four lines of evidence leading to the conclusion that a notable fraction of the ionizing photon emission from the stars within H II regions in the disks of normal galaxies escapes from the regions into the surrounding galaxy and beyond. These are: (1) The surface brightness intensity distribution of the diffuse Hα emitted by a disk galaxy is well modeled by assuming that the Lyman continuum producing it leaks from the H II regions. (2) The relation of the central Hα surface brightness to total luminosity of an H II region departs from the predictions of uniform ionization bounded systems. (3) The Hα luminosity function of complete H II region populations shows a break whose parameters are explicable using the density bounding hypothesis, but not via competing hypotheses. (4) The relation between the Hα internal velocity half–width and luminosity for H II regions is naturally explained via density bounding. A fractally clumpy cloud structure, and a simple law relating the mass of the most luminous star in a young cluster to the mass of its placental gas cloud give model parameters which can account for the observations. We show how the fraction of the Lyc escaping from leaky H II regions which finally completely escapes the galactic disks can ionize large volumes of the ultra–low density intracluster gas around galaxies.

Key Words: **GALAXIES: ISM — GALAXIES: SPIRAL — ISM: GENERAL — ISM: H II REGIONS**

1. THE IMPORTANCE OF THE DIFFUSE Hα COMPONENT

An image of a "normal" disk galaxy taken in Hα emission (normally an image through an Hα filter, from which a neighboring continuum image is carefully subtracted) reveals the obvious star forming zones as areas of high surface brightness: classical H II regions. However, there is a low level background of diffuse Hα which looks unimportant, but which has been shown to comprise some 50% of the total Hα luminosity of a typical late–type galaxy (Zurita et al. 2000), occupying over 80% of the disk area. The origins of this component have been discussed and solutions proposed. These include:

(a) Disseminated ionizing emission from white dwarfs, including the central stars of planetary nebulae.

(b) A "carpet" of weak overlapping H II regions.

(c) Decaying massive neutrinos, which give rise to ionizing photons.

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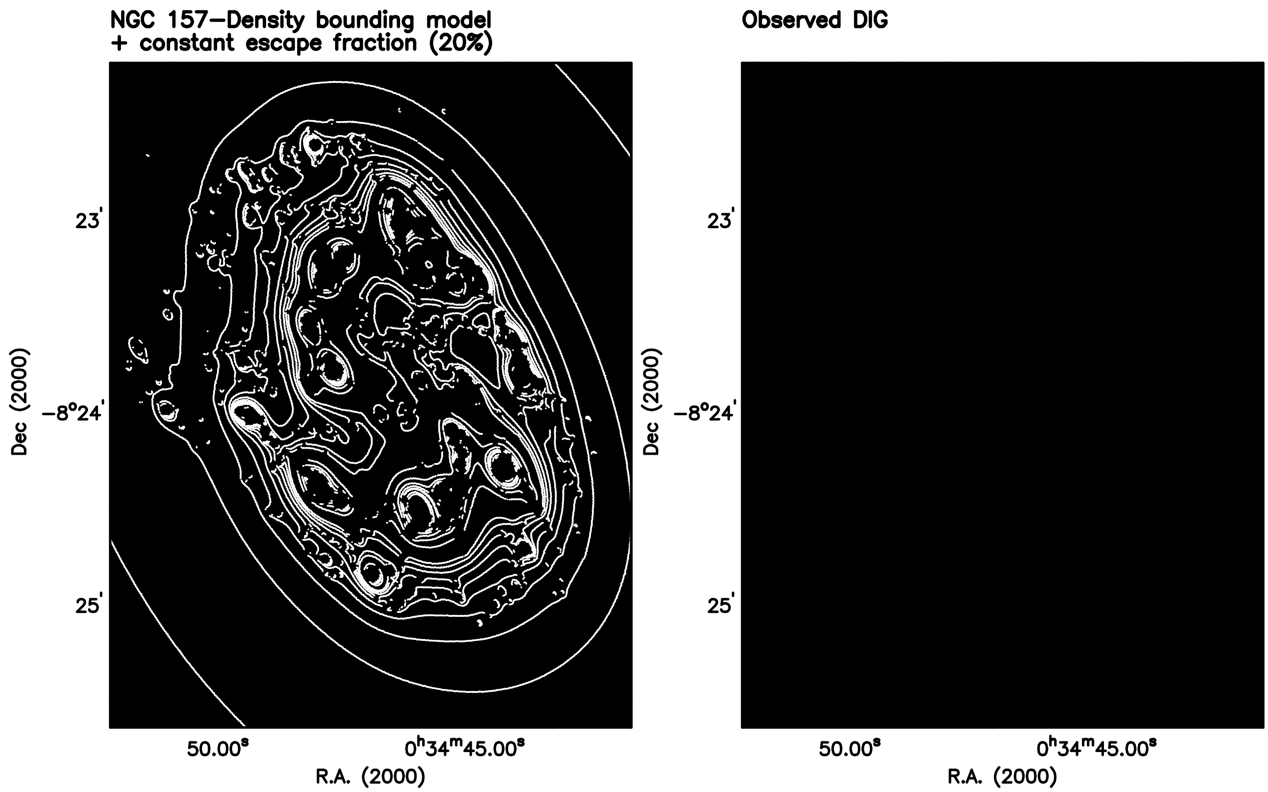

Fig. 1. The DIG, Hα surface brightness in NGC 157. Observed distribution compared with a model based on ionization mechanism (b), showing how this can account well for the observed distribution. For further details see Zurita et al. (2002b).

(d) Escaping photons from major, luminous H II regions.

(e) Conversion of large scale mechanical energy to Hα emission.

The tests which any proposed mechanism must pass are:

(i) Can the source supply enough energy globally?

(ii) Are the sources capable of delivering the ionizing photons to distant parts of the diffuse ionized gas (DIG)? This is particularly a problem for source (d), where the nearest luminous H II region may be over a kpc away from the emitting DIG.

Best estimates show that source (a) falls well short of the overall power requirement for a galaxy, but it might be relevant well above the plane of a galaxy, where an older local population of white dwarfs can illuminate a relatively tenuous part of the DIG. This will not contribute in a major way to the integrated Hα surface brightness viewed in a face on galaxy. Considering mechanism (b), the only galaxies for which luminosity functions (LFs) with H II regions in the range significantly below $L_{\mathrm{H}\alpha} = 10^{36}$ erg s^{-1} have been measured are M31 (Walterbos & Braun 1992) and M33 (Cardwell et al. 2000).

M33 is a flocculent spiral, with morphology very different from the classical grand design spirals we are generally dealing with. It is strongly affected by its interaction with the more massive M31. Thus its H II region LF, which shows a steady rise in numbers down to the detection limit of 10^{34} erg s^{-1}, should not be considered representative. In this object it is difficult to bound the arms, but in any case its diffuse component is clearly due to weak overlapping H II regions, which can be detected directly in the Hα image. However, for M31 this is clearly not the case, and its LF flattens below 10^{36} erg s^{-1}. Here the DIG cannot be due to a carpet of weak H II regions, and we take this result as typical of the galaxies we have studied. In these, in general mechanism (b) cannot dominate, and must contribute very little.

This implies that isolated roving O or B stars will not cause the bulk of the DIG, Sciama's (1990) decaying neutrino hypothesis was ingeniously designed to account for the difficulty of long distance propagation, which was avoided by these *in situ* sources of ionizing photons. However, the failure to detect this radiation by the EURD (Bowyer et al. 1999) space experiment, plus the fact that it was seen as ad hoc by the theorists, seems to have removed mechanism (c) from serious consideration.

Mechanism (d), that of escaping photons from luminous H II regions can well pass test (i), in the sense that the OB stars in these regions emit sufficient ionizing energy to account for the globally observed diffuse Hα. However, there are two doubts to settle. Can a sufficient fraction of the photons escape from the regions, and can they penetrate the H I to distances of $\sim$ 1 kpc? This is essentially test (ii) expressed in more detail. It is well known that H II regions are clumpy, fractal–like in their density distributions, (Osterbrock 1989) since observed mean values of their electron densities, estimated via emission measures in Hα, are two orders of magnitude lower than *in situ* values, estimated from emission line ratios. This implies that all H II regions are leaky; however, we have shown (Rozas et al. 1996; Beckman et al. 2000) that the more luminous regions appear to be leakier, with a higher escape fraction of Lyman continuum flux. Using a parametric formulation for the escape fraction, described in Zurita et al. (2002, these proceedings), we have modeled the impact of the escaping Lyc on the surrounding hydrogen, for NGC 157 and shown that mechanism (d) is capable of yielding not only the global energy in the DIG, but also its spatial distribution (Zurita et al. 2002b). The details of the transport on kpc scales remain to be explored in realistic models, but as pointed out by Dove & Shull (1994) and by Miller & Cox (1993) the key to this process is a combination of clumpiness and the fact that at the low densities prevailing, the ionization of the medium renders it transparent on relatively long timescales.

The mechanism (e), that of mechanical friction, may be important in accounting for the high ionization states found in the DIG, notably in our Galaxy where it has been measured with some spatial detail. However, it is likely to be more important far from the plane of a galaxy, and in any case the effective hardness of the radiation implied might be accounted for simply by the process of radiative transfer over long distances from the H II regions, since the photoionization cross–section varies inversely as the cube of the frequency, measured from the Lyman limit frequency as zero point. So we leave as an open question the importance of mechanisms (e) and (a) in the ionization of the DIG, while pointing out that mechanism (b) can potentially produce the whole ionized DIG volume. Detailed modeling using mechanism (b) is presented in Zurita et al. (2002b). One of the family of models from that paper is shown in Figure 1.

2. H II REGION CENTRAL SURFACE BRIGHTNESS

In a classical ionization bounded H II region, it is easy to show that the central surface brightness should be proportional to the cube root of the total luminosity of the region. This is strictly true for regions of uniform density and filling factor. With the same assumptions, the volume of a region should be proportional to the luminosity (or the cube root of the volume to the radius, which is equivalent). Similar relations would hold for leaky H II regions, provided that their geometries were self-similar, i.e., that the escape factor due to clumpiness remains constant independently of the luminosity of the region. Our observations have shown that the surface brightness –luminosity and volume–luminosity relations predicted above do in fact hold for H II regions over a wide range of luminosities, but appear to break down at luminosities above the critcal value $L_{\mathrm{H}\alpha} = 10^{38.6}$ erg s^{-1}, which we have termed the Strömgren luminosity L_{Str} (Beckman et al. 2000). Figure 2 shows this in terms of the central surface brightness. The effect plotted in terms of volume is less striking (Rozas et al. 1996, 1999, 2000) presumably because the radius of any H II region is a weak observable, depending as it does on low surface brightness components, blending into the DIG. Figure 2 presents evidence of a change in H II region properties at $L_{\mathrm{H}\alpha} = L_{\mathrm{Str}}$. The effect is not an artefact due to angular resolution because:

(1) The smallest regions sampled had 3 pixel diameters, which make them comparable with the resolution in the images.

(2) The transition occurs at the same luminosity in all the galaxies, in spite of a distance range of a factor almost 5 between the nearest and the farthest.

(3) Any plausible hypothesis about the true brightness distribution of the family of regions would not yield the observed behavior, in which the increase in surface brightness is steeper for $L_{\mathrm{H}\alpha} > L_{\mathrm{Str}}$, and on any hypothesis the observed change in the surface brightness vs. luminosity relation

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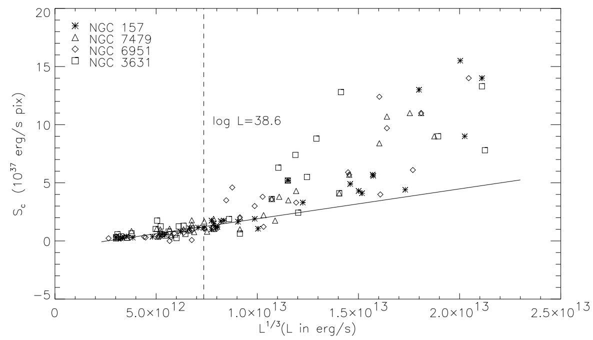

Fig. 2. Central surface brightness vs. Luminosity$^{1/3}$ for selected H II regions in a set of spiral galaxies. Note the linear dependence at lower $L_{\mathrm{H}\alpha}$ and the sharp departure at high $L_{\mathrm{H}\alpha}$. These effects cannot be explained as resolution artefacts (see text).

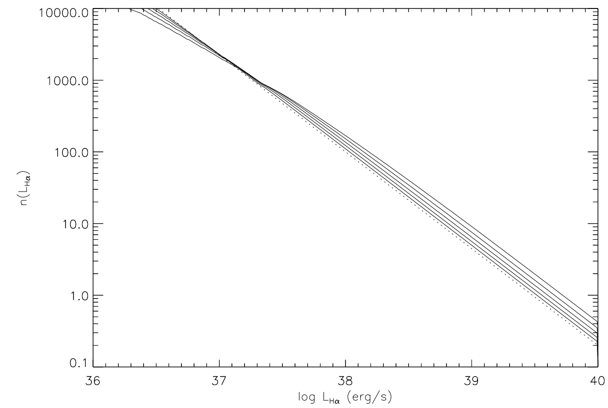

Fig. 3. The effects of low resolution smearing on the Hα LF of H II regions in a disk galaxy. The initial LF is a power law (dashed line) and the effects of degrading the resolution appear as continuous lines. Note that above a critical luminosity the LF slope is reduced by smearing and not increased as found observationally.

must imply an underlying change in the properties of the H II regions.

It is easy to show (and Strömgren himself (1939) offered a proof of this), that this change cannot be due to a change in the number of luminous ionizing stars at the centre of the region. Any such change would not, if the surrounding medium has essentially invariant properties, affect the surface brightness vs. luminosity relation, in an ionization bounded H II region. It is also very clear that the increase in the surface brightness/luminosity ratio above $L_{\mathrm{H}\alpha} = L_{\mathrm{Str}}$ is not consistent with an explanation of the change in terms of dust extinction; using a conventional constant dust to gas ratio assumption. We will return to this point below.

3. STATISTICALLY COMPLETE H II REGION LUMINOSITY FUNCTIONS

In a series of papers (Rozas et al. 1996, 1999, 2000; Beckman et al. 2000) we have shown that the luminosity functions of H II regions, measured in Hα, of disk galaxies suffer a change in slope, normally accompanied by a local peak, at $L_{\mathrm{H}\alpha} = L_{\mathrm{Str}}$. Although only a limited number of galaxies have been measured in this way, the change (Fig. 5) appears in all the LF's obtained so far. We have shown that the hypothesis of a transition to increased photon leak at $L_{\mathrm{H}\alpha} = L_{\mathrm{Str}}$ offers a natural explanation for a drop in slope, accompanied by a local peak. Regions which, according to their massive stellar content, would have had Hα luminosities of a given value in the range $L_{\mathrm{H}\alpha} > L_{\mathrm{Str}}$, have reduced luminosities, as a fraction of their Lyc photons escapes. An underlying physical basis for this is a dependence of massive star formation efficiency on placental cloud mass producing a total Lyc photon luminosity which rises more steeply than linearly as a function of cloud mass. This is, physically, entirely plausible (Beckman et al. 2000).

Alternative hypotheses might explain these observations, but it is not easy to find one that in fact does this. One explanation, suggested recently by Pleuss et al. (2000) is that a combination of spatial clustering and insufficient angular resolution may lead to an artificial change in slope of the LF. In Fig. 3 we present results from a simulation in which this idea was tested. An LF with a natural power law was subjected to an overlap procedure, in which small regions were absorbed by larger ones, simulating the effect of smearing at finite resolution. It is easy to see that the LF slope does in fact change at a specific luminosity (which depends on the adopted mean separation of the regions). However, the change in slope is in a contrary sense to that observed, and there is no indication of a peak. Further, any effect due to the angular resolution would show up at a luminosity dependent on the distance of the galaxy, and our observations show that this is not the case.

A further possible cause of the observed change in slope might be dust extinction within the H II regions. Here again a quantitative examination, rather than a simple verbal suggestion, shows that it is improbable that dust causes the effect. In Fig. 4 we have modeled the changes to the observed LF due to introducing dust into a family of H II regions. The

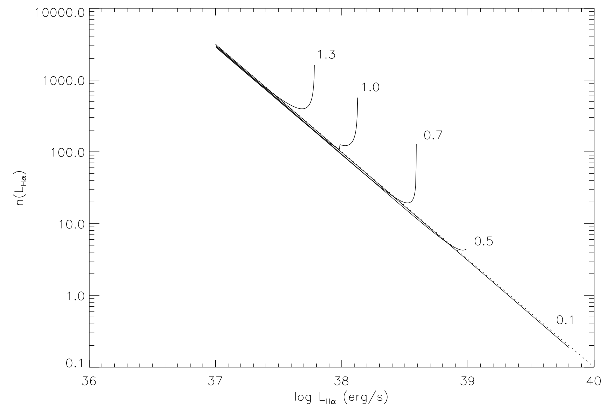

Fig. 4. Modeling the effect of internal dust on the LF of H II regions in a disk galaxy. The original power law (dashed straight line) is modified by the introduction of an increasing dust fraction specified by the optical depth for 100 pc pathlength. Note the LF cut–offs in all models. Without major modifications (see text) these models cannot explain the observations.

curves are for increasing dust content, at constant dust to gas ratio. They show that an LF with a power law distribution with no dust is modified to yield a high luminosity cut-off accompanied by a terminal peak, as the emitted Hα is limited by extinction. These LF's do not reproduce the observations. Further, applying the same models to the surface-brightness vs. luminosity plot we would find a decrement in surface brightness for $L_{\rm H\alpha} > L_{\rm Str}$ rather than the increment observed. It is just possible that some sort of finely tuned model, in which the dust content increases with luminosity up to a critical value, near $L_{\rm H\alpha} = L_{\rm Str}$, and is then blown or sputtered out could explain the observations. However, this would anyway give rise to the enhanced Lyc photon leak which is the basic premise of the present article. Finally, the model of Oey & Clarke (1998), in which the change in LF slope is explained as due to the effect of a transition from single star to multiple star ionization, predicts a change at values of L some 2.5 times below the observed value of $L_{\rm Str}$, does not yield a local peak in the LF, and does not yield the observed increment in surface brightness at high $L_{\rm H\alpha}$.

4. THE INTERNAL TURBULENT MOTIONS, VIRIALITY AND PHOTON ESCAPE

In a paper in which the internal turbulence of a complete set of H II regions was examined in M100 (Rozas et al. 1998) we were searching for evidence of the presence or absence of virial equilibrium. We

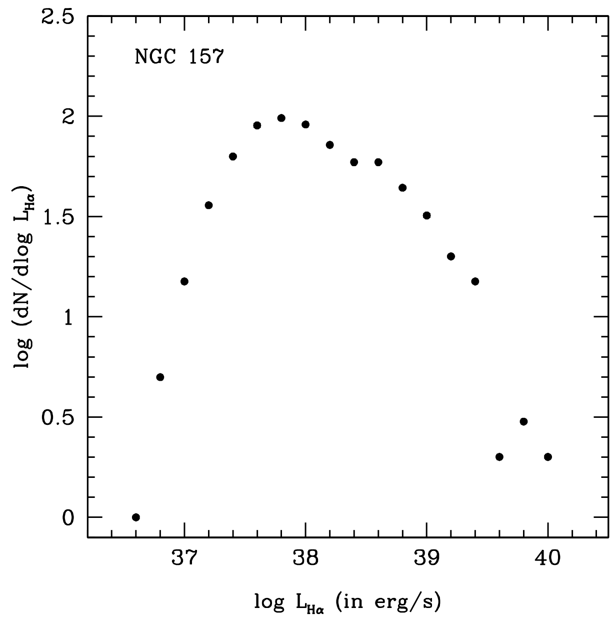

Fig. 5. Luminosity function in Hα for the complete sample of H II regions in the NGC 157 catalogue. This is characteristic of all the galaxies observed to date.

found that the expected relation, in which the luminosity of a region varies as the fourth power of its turbulent velocity width was not obeyed. However, we noted that the lower envelope in velocity width was very well defined. This did not, in the log–log plot (see Fig. 6) have slope 4, but a slope close to 2.5. A similar result was also reported for M101. A natural explanation for this slope is that an increasing fraction of the ionizing photons produced in the regions escape as the luminosity of a region increases. The measurements all relate to the range in luminosity $L_{\rm H\alpha} > L_{\rm Str}$, since lower values of the velocity width were not reliable, due to the effects of thermal and instrumental broadening. It is clearly important to expand the data base on which any firm conclusion is drawn, but these results also have a natural explanation in a scenario where a major fraction of the Lyc photons escape from high luminosity H II regions.

5. CONCLUSIONS

We have brought together four lines of evidence which converge to imply that H II regions are leaky in ionizing photons, and that there is a trend to increasing leakiness at high luminosity. The photometric measurements and reductions were all performed with especial rigor, the majority being results from a camera (TAURUS) of exceptional optical cleanliness, in which the narrow band interference filters are

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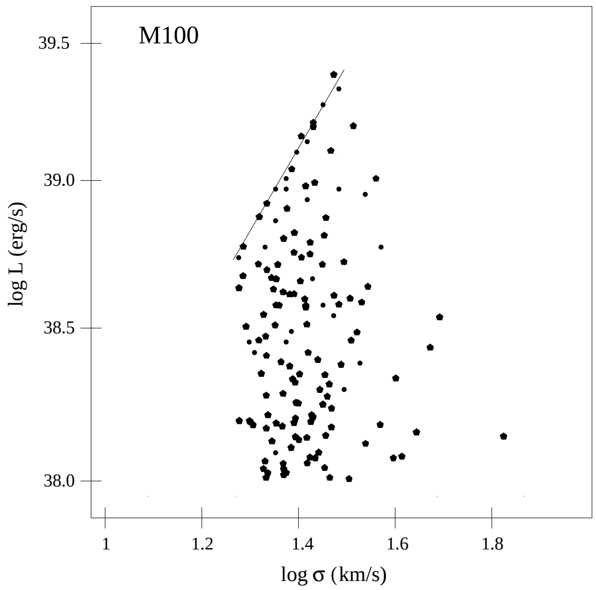

Fig. 6. Log-log plot of internal turbulence half–widths (σ) vs. Hα luminosity (L) for the 200 brightest H II regions in M100. Note the envelope, which represents regions in virial equilibrium. Its slope of 2.6 can be explained if an increasing fraction of ionizing photons escapes from the regions as their luminosity increases.

traversed by parallel radiation, and in which Hα is isolated from the nearby N II doublet, on a site with outstanding seeing. We have examined the possibility that some of the effects reported might be artefacts due above all to the effects of resolution and have shown quantitatively and qualitatively that this is improbable.

As well as accounting for the diffuse Hα in galaxy disks, our model predicts that normal galaxies may well release up to 20% of their ionizing photons into their intracluster and intergalactic environments (Zurita et al. 2002b). As the mean atomic densities are so low there, a relatively minor photon escape from normal galaxies might well be enough to ionize major volumes and masses of the intergalactic medium, without reference to especially energetic events (starbursts, AGN's) (Zurita 2001). There should also be implied corrections to galaxy star formation rates based on Hα luminosities.

Naturally it will be important to test the scenario using alternative evidence. Line ratio maps in ions sensitive to the density bounding condition are contemplated, and the first observations have already been obtained. Fuller treatment of the propagation of ionizing photons in inhomogeneous media, going beyond the work of Dove & Shull (1994) will be needed for adequate interpretation of observed results.

Finally we point out that the transition at L_{Str} occurs at a high emission luminosity, concentrated into a single spectral line. Its low variance in the galaxies so far observed implies that it should serve as a useful and rather precise standard candle well out into the Hubble flow.

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