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OBSERVATIONAL CONSTRAINTS ON DWARF GALAXY EVOLUTION: A RETROSPECTIVE OF LEQUEUX ET AL. (1979)

Evan D. Skillman

Astronomy Department, University of Minnesota

RESUMEN

Las contribuciones de los Peimbert han sido fundamentales para establecer ideas concernientes tanto a las propiedades como a la evolución de las galaxias enanas. Revisaré brevemente estas ideas dentro del contexto de una retrospectiva del artículo histórico "Chemical Composition and Evolution of Irregular and Blue Compact Galaxies" de Lequeux, Peimbert, Rayo, Serrano, & Torres-Peimbert, 1979, A&A, 80, 155. Este artículo aportó observaciones espectroscópicas pioneras de regiones H II en 6 galaxias enanas y proporcionó muchas de las bases de nuestra visión moderna de las galaxias enanas. La mayoría de las conclusiones e inferencias permanecen válidas hoy, a dos décadas de su publicación.

ABSTRACT

Contributions by the Peimberts have been fundamental in establishing ideas concerning both the properties and the evolution of dwarf galaxies. I will briefly review these ideas within the context of a retrospective of the milestone paper: "Chemical Composition and Evolution of Irregular and Blue Compact Galaxies" by Lequeux, Peimbert, Rayo, Serrano, & Torres-Peimbert, 1979, A&A, 80, 155. This paper added pioneering spectroscopic observations of H II regions in 6 dwarf galaxies and provided much of the basis of our modern view of dwarf galaxies. Most of the conclusions and inferences remain true today, over two decades since they were written.

Key Words: **GALAXIES: ABUNDANCES — GALAXIES: DWARF — GALAXIES: EVOLUTION — GALAXIES: INDIVIDUAL (I ZW 18) — GALAXIES: IRREGULAR — H II REGIONS**

1. INTRODUCTION

My notification of this conference included an invitation to talk on "dwarf galaxies," and, at the time, that seemed a very reasonable thing to do. However, while checking on a reference in the ADS, I discovered that Manuel and Silvia had written a retrospective article for the ApJ Centennial Issue on "Peebles' Analysis of the Primordial Fireball" (Peebles 1966). Well, this got me to thinking. First off, I was curious as to how many citations were registered for the Peebles article (since this appears to be how we measure the importance of articles these days). The ADS listed 78 citations for the Peebles article. Then I wondered how it measured up with one of my personal favorites: "Chemical Composition and Evolution of Irregular and Blue Compact Galaxies" by Lequeux, Peimbert, Rayo, Serrano, & Torres-Peimbert, 1979, A&A, 80, 155 (hereinafter L79). For this article I found the ADS lists 345 citations. This is an impressive number, and confirms my prejudice that this is a truly great paper[1].

Figure 1 displays a histogram of the history of citations to L79. One can see that this paper is still being cited at a respectable rate over 20 years after it first appeared in press. Because I share with Manuel and Silvia a passion for the determination of the primordial helium abundance, I have a program which derives linear least squares fits to data. I took the histogram data, assigned errors of ± 1 to both years (to allow for the uncertainty due to editors and publishers for the year in which the paper should have appeared) and the number of citations appearing in a given year, and the least squares fit resulted in a slope of -0.754 ± 0.062 with an intercept of 24.68 ± 0.75. This predicts that this paper will enjoy citations at least through the next decade, and quite possibly on into the next. The fit is overplotted on the histogram in Figure 1. The fit is not especially good, and the χ^2 of 325 fully justifies fitting a higher order function, but the exercise got the desired laughs at the conference, and I didn't feel that I should pursue the higher order terms.

[1] As a point of interest, Bernard Pagel speculated that the reason for the relatively low number of citations to the Peebles paper was the appearance of the paper by Wagoner, Fowler, & Hoyle (1967). As usual, Bernard's speculation finds support from the data; the ADS lists 216 citations to the Wagoner et al. (1967) paper.

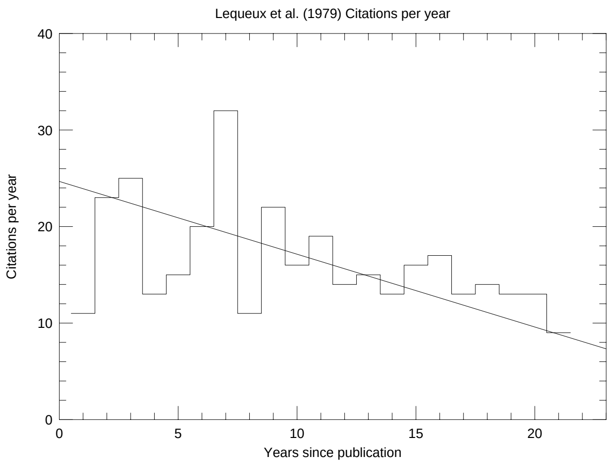

Fig. 1. A histogram plot of the number of citations per year to the Lequeux et al. (1979) paper as a function of the number of years since publication. (Citations counted from those reported by the ADS.) Two features are notable. First, the overall large number of citations (345), and second, the rather level number of citations 15 to 20 years since the date of publication. Both are taken as evidence of a paper of significant importance. The solid line is a linear, least squares fit to the data which was performed solely for entertainment value.

The appreciation that this paper represents a milestone in the research of dwarf galaxies led me to attempt a retrospective for this conference. Note that I am handicapped in that in 1979, the year of publication, I had just started graduate school. Thus, I cannot provide a true historical perspective. It is possible that some of the results and ideas contained in this paper were appearing in other papers at the time, and all of this knowledge came to me only through this vehicle. If so, I apologize in advance to all those who might take offense. From the first footnote of the paper, I do note that the lead author (who I referred to as "Juan" Lequeux at the conference—which received the biggest laugh) was on leave from the Observatoire de Meudon when this paper was written, joining the other four authors at UNAM.

2. THE OBSERVATIONS

The new observations presented in L79 consisted of optical spectra from the KPNO 2.1-m telescope using the IIDS. Eight H II regions were observed in six different dwarf irregular and blue compact galaxies (NGC 4449, NGC 6822, IC 10, II Zw 70, II Zw 40, and I Zw 18). Part of the "staying power" of this paper can be understood from the choice of galaxies. This paper provided a relatively high quality spectrum for I Zw 18, a galaxy which continues to be frequently observed to date. The spectra for IC 10 have provided chemical abundance estimates for this galaxy, whose H II regions have been more-or-less ignored over the ensuing two decades (Michael Richer informed me that this situation has been remedied in the last year, and a new study is in press). In terms of perspective, the business of collecting emission line spectra has been greatly improved with the advent of the large format, linear CCD detectors. These allow us to collect very high signal-to-noise spectra and to estimate the errors associated with the emission line ratios quite accurately (as compared to the IIDS with relatively large apertures and non-linearities). Nonetheless, the abundances reported in L79 have withstood the test of time and compare quite favorably with modern values.

3. CHEMICAL COMPOSITIONS

Chemical abundances for oxygen, nitrogen, and neon were derived for all observed H II regions, covering a range of about 20 in metallicity. Abundances were calculated using assumptions of both no temperature variations and temperature variations of order those determined for the Orion nebula (Peimbert & Torres-Peimbert 1977; i.e., $t^2 = 0.035$); debates concerning this assumption continue on to date (see the contribution by Esteban 2002 in these proceedings).

The large baseline in metallicity allowed an extension of the method of Peimbert & Torres-Peimbert (1974, 1976) to determine the primordial helium abundance ($Y_{\rm p}$). This method of determining the regression of helium abundance as a function of metallicity remains the primary technique for determining $Y_{\rm p}$. A value of $Y_{\rm p} = 0.233 \pm 0.005$ was derived from combining all existing extragalactic data. This value is in agreement with the modern value of 0.2345 ± 0.0026 derived by Peimbert, Peimbert, & Ruiz (2000), but is low compared to the value of $Y_{\rm p} = 0.2452 \pm 0.0015$ favored by Izotov and his collaborators (Izotov & Thuan 1998; Izotov et al. 1999). The differences between the two modern values are due more to the method of analysis than to the observational data, and this stands as a major challenge for observational cosmology (Skillman 2001).

The relationship between oxygen and nitrogen abundances was investigated through a plot of N/O versus O. In this plot, the data show a good degree of scatter (although the eye has been guided by overlaying chemical evolution models with varying degree of mass loss). The source of this scatter in the N/O versus O relationship has remained a challenge for evolution modelers ever since. Garnett (1990) argued convincingly that most of the scatter

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
Editors: William Henney, José Franco, Marco Martos, & Miriam Peña

in N/O at a given O was real, and not related to observational errors (although measuring N/O accurately does present observational challenges). I will return to this diagnostic diagram in § 6.

4. MASSES, Z VERSUS $M_{\rm tot}$ RELATION, AND YIELDS

L79 was published just as the importance of dark matter halos in galaxies was beginning to be appreciated (Bosma's thesis appeared in 1978, and his refereed publications of his thesis work in 1981). Later H I synthesis observations of dwarf irregular galaxies and blue compact galaxies revealed that many of these systems were dominated by dark matter (e.g., Carignan & Freeman 1988). Thus, while the authors of L79 felt confident that they could measure masses from H I synthesis observations of some of the sample, they did not know that these masses corresponded to large amounts of potentially nonbaryonic material. This is key when trying to estimate yields.

The first result was a clear correlation when comparing metallicity with mass. This relationship has been confirmed (usually in the form of a metallicity-luminosity relationship) by numerous studies (e.g., Talent 1980; Kinman & Davidson 1981; Skillman, Kennicutt, & Hodge 1989; Richer & McCall 1995; van Zee et al. 1997), and is found to be true for essentially all types of galaxies (see Zaritsky, Kennicutt & Huchra 1994 and references therein). Note however, that this relationship is not without controversy (Hidalgo-Gamez & Olofsson 1998; Hunter & Hoffman 1999).

Following Schmidt (1963) and Searle & Sargent (1972), L79 pointed out that, in principle, if (a) galaxies behaved as well-mixed closed systems and (b) the IMF and nucleosynthesis are universal, then by using an element such as oxygen, for which the instantaneous recycling approximation is reasonably realistic, one could derive a simple relationship between the gas mass fractions and chemical abundances (and thereby determine chemical yields). L79 found a reasonably linear relationship between Z and $\ln(M_{\rm gas}/M_{\rm tot})$ supporting the viability of their analysis. The derived value of the yield supported current estimates from stellar evolution models which included mass loss due to stellar winds (Chiosi, Nasi, & Sreenivasan 1978; Chiosi, Nasi, & Bertelli 1979). There has been a tremendous degree of progress in this field in the last two decades. While the details have changed in great degree (a major factor was the recognition of the role of dark matter, but there have been many other advances too numerous to list here) the method of comparing fractional gas masses to observed abundances remains the basis of our testing of the theoretical yields.

5. MODEL CALCULATIONS OF CHEMICAL EVOLUTION OF IRREGULAR GALAXIES

Models of chemical evolution were run in order to fully exploit the new database. Codes originally written by Vigroux and collaborators (Vigroux et al. 1976; Alloin et al. 1979) and Serrano (1978) were combined and updated. These models incorporated the latest version of the initial mass function (Lequeux 1979; Serrano 1978) and the most recent stellar evolution models where the effects of mass loss had been accounted for (Chiosi 1979; Chiosi & Cammi 1979; Chiosi et al. 1978; 1979). In retrospect this all sounds rather familiar to today's exercises. The debate on the true nature of the IMF continues with small revisions continuing to appear (cf. Gilmore & Howell 1998) and the models of stellar evolution continue to grow in sophistication (cf. Chiosi 1998; Maeder 2000).

The chemical evolution models relaxed the assumption of instantaneous recycling, which allows for the delay in enrichment due to the lifetimes of stars. Constant star formation rate models were considered.

6. COMPARISON WITH OBSERVATIONS

The true impact of the paper comes through the comparisons of the model calculations with the observations. There is very reasonable agreement between the models and the trend line between metallicity and gas mass fraction. That is to say that models with mass loss and reasonable values for yields reproduce the data nicely. It is still true today that mass loss is required to understand the oxygen yields of massive stars. The best constraint comes from observations of the C/O ratio, and modern studies indicate that C and O production are dominated by the massive stars, while the yields are metallicity dependent due to the increasing effects of winds with increasing metallicity (Maeder 1992; Garnett et al. 1995; Gustafsson et al. 1999; Carigi 2000).

The calculation of the ratio of helium enrichment to heavy element enrichment ($\Delta Y/\Delta Z$) is derived observationally from the plot of Y versus O/H and theoretically from the stellar evolution models. A value of roughly 2 was found observationally. A large range of values can be found theoretically due to sensitivities to both mass loss by stars and the evolutionary time differences between the stars that produce the bulk of the heavy elements (massive stars) and the stars that produce the bulk of the helium

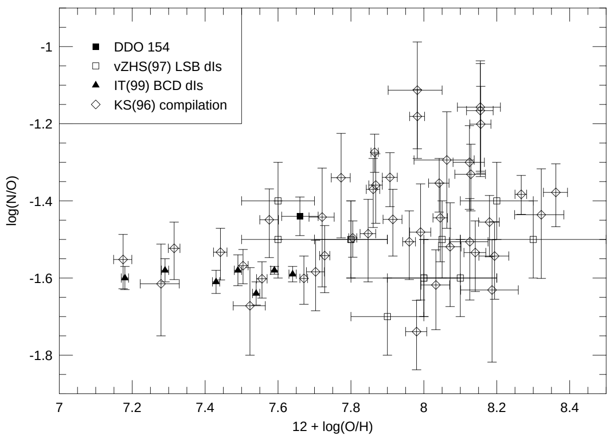

Fig. 2. A comparison of the N/O and O/H in DDO 154 with the collection of dwarf irregular galaxies and H II galaxies assembled by Kobulnicky & Skillman (1996; see their Table 5 and Figure 15 for identification of individual points). Only galaxies without WR emission features and errors in log (N/O) less than 0.2 have been plotted. The filled square symbol with error bars represents DDO 154. The empty square symbols represent the data of van Zee et al. 1997, and the filled triangles represent the low metallicity BCDs from Izotov & Thuan (1999). (from Kennicutt & Skillman 2001)

(intermediate mass stars). In order to get values close to the observationally favored value of $\Delta Y/\Delta Z$, L79 concluded that both stellar mass loss and large galaxy lifetimes (comparable to a Hubble time) are required. The situation is not so clear today. Izotov & Thuan (1998) find a value of $\Delta Y/\Delta Z = 2.4 \pm 1.0$ from observations of blue compact galaxies, while Peimbert et al. (2000) find $\Delta Y/\Delta Z = 3.5 \pm 0.9$ for irregular galaxies. One may take some comfort in the fact that these two measures are not that far apart. However, taken at face value, the large range covered by the two (from 1.4 to 4.4) provides only mild constraints on the stellar evolution models. Note also that galactic winds are now thought by many to play an important role in the evolution of dwarf galaxies. Differential (or selective) winds will alter the observed value of $\Delta Y/\Delta Z$. For this reason, Pagel et al. (1992) proposed that using nitrogen for the basis of the metallicity determination (as opposed to oxygen) could be preferable (and the data appear to support this, see their discussion).

In L79, for the first time, the variation of abundance of N and O had been measured in enough dwarf galaxies to begin a comparison. Although the diagram showed a great deal of scatter, a model with an initial nitrogen-to-oxygen ratio of $\log(\mathrm{N/O}) = -1.7$ (due to primary nitrogen) and a secondary nitrogen component increasing with increasing metallicity appeared to fit the trend well. The origin of nitrogen has continued to be a long standing problem in astrophysics (Edmunds & Pagel 1978; Vila-Costas & Edmunds 1993; Henry, Edmunds, & Köppen 2000). A modern compilation of N/O versus O/H in metal poor H II regions is shown in Figure 2. The data conform to the trend seen by L79, although the interpretation offered by Henry et al. is quite different. Recently, Izotov & Thuan (1999) have derived an average of -1.60 ± 0.02 for a sample of 6 BCGs with $12 + \log(\mathrm{O/H}) \leq 7.6$. The remarkably small dispersion in N/O leads them to argue that all galaxies with $12 + \log(\mathrm{O/H}) \leq 7.6$ are less than 40 Myr old. This would appear to conflict with observations of galaxies like Leo A which has $12 + \log(\mathrm{O/H}) \approx 7.4$ (Skillman et al. 1989; van Zee, Skillman, & Haynes 1999), but a well developed red giant branch consistent with star formation over at least the last 2 Gyr (Tolstoy et al. 1998).

L79 discuss the differences between blue compact and irregular galaxies. The obvious difference is the heightened star formation rate in the blue compacts; the key question is whether blue compacts have older, underlying stellar populations like the irregular galaxies. L79 proposed that offsets between blue compacts and dwarf irregulars in the Y vs. O/H and the N/O vs. O/H diagrams would be predicted by different overall ages. They note that with the quality of their data it is not possible to distinguish the two classes of galaxies. However, they do favor the interpretation that the blue compacts are not inherently young galaxies, but are probably very similar to irregular galaxies with temporarily heightened star formation rates. This view is now being confirmed with resolved stellar population studies of blue compact and dwarf irregular galaxies (e.g., Lynds et al. 1998; Dohm-Palmer et al. 1998).

A key failing of the models was their inability to explain the large mass-to-light ratios for the sample. Values of M_{tot}/L_B ranged between 3 and 5 in solar units for the irregular galaxies and of order 1 for the blue compact galaxies. The models predicted values of 0.5 or less. L79 noted that Rubin, Thonnard, & Ford (1978) were finding a similar discrepancy for Sc galaxies (and Bosma's Ph.D. thesis 1978 shows that the relative amount of "darker material" increases with increasing radius in the spiral galaxies). L79 offer an explanation that the masses of the dwarf galaxies may have been overestimated. With hindsight, it appears that the baryonic masses may have been overestimated as they may represent only a fraction of the total masses of the galaxies. The

Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
Editors: William Henney, José Franco, Marco Martos, & Miriam Peña

last three sentences of the paper appear quite prescient:

> "The M/L ratios, particularly those for the irregular galaxies, are higher than those predicted by the models. This discrepancy diminishes if the average luminosity of these objects was higher in the past. This problem should be studied further."

By emphasizing the discrepancy between observations and models (as opposed to minimizing the differences in order to strengthen the other conclusions), this paper gives a foreshadowing of another important turning point in astrophysics.

7. CONCLUSIONS

Are there additional lessons to be learned from this paper? The observations, although making use of a relatively new technology (the IIDS detectors), did not require an inordinate amount of time and were not even taken on the largest telescope available (the 2.1-m at KPNO). The strengths of the paper, while starting with the pioneering nature of the observations, probably lie closer to the combination of these data with the contemporary thoughts on stellar evolution, nucleosynthesis, and galactic evolution modeling. Most of the conclusions of the paper have been supported by a myriad of observations collected in the intervening decades.

Almost every time I meet Manuel at a conference, he has the occasion to remind me of some favorite advice from George Herbig—"If a paper is found to have no flaws five years after publication, it should be taken out of the literature and put into a museum." Clearly very few papers belong in museums, but this one comes close.

I would like to thank the conference organizers for inviting me to such wonderful meeting. I would also like to thank Bernard Pagel for several valuable suggestions on an earlier draft. My research on dwarf galaxies is supported, in part, by a NASA Long Term Space Astrophysics grant (NAG5-9221) and by the University of Minnesota.

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Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
Editors: William Henney, José Franco, Marco Martos, & Miriam Peña

María Teresa Ruiz and Silvia Torres-Peimbert

Evan D. Skillman: Astronomy Department, University of Minnesota, 116 Church St. SE, Minneapolis, MN, 55455, USA (skillman@astro.umn.edu).