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THIRTY YEARS OF EXTRAGALACTIC H II REGION STUDIES

D. R. Garnett

Steward Observatory, University of Arizona

RESUMEN

Reviso parcialmente los estudios de regiones H II extragalácticas en los pasados treinta años. Comparando los resultados disponibles en 1975 con lo que sabemos hoy, vemos un enorme incremento de nuestro conocimiento de las condiciones físicas y abundancias en las regiones H II extragalácticas, la evolución química de las galaxias, y la fracción de helio primordial. Manuel Peimbert y Silvia Torres-Peimbert han hecho contribuciones pioneras a este campo. Aquí delineo el progreso en nuestro entendimiento de las regiones H II extragalácticas y remarco las contribuciones de los Peimbert.

ABSTRACT

I review a small part of the past thirty years of studies of extragalactic H II regions. Comparing a review of available results in 1975 to what we know today, we see a enormous increase in our knowledge of physical conditions and abundances in extragalactic H II regions, chemical evolution of galaxies, and the primordial helium fraction. Manuel Peimbert and Silvia Torres-Peimbert have made pioneering contributions to this field. Here I outline the progress in understanding extragalactic H II regions and highlight the Peimberts' contributions.

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

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1. INTRODUCTION

Extragalactic H II regions (in particular, giant H II regions or GHRs) have played an important role in our understanding of chemical evolution in spiral and irregular galaxies. GHRs trace the young, massive star component in galaxies, illuminating and ionizing cubic kiloparsec sized volumes of interstellar medium (ISM) with UV radiation. H II regions emit forbidden lines from a variety of heavy elements (including C, N, O, Ne, Si, S, and Ar, among others). With appropriate constraints on physical conditions, one can derive ionic and element abundances and thus study the composition of the ISM. Because the ISM efficiently converts UV ionizing radiation into a few narrow emission lines, GHRs can be very luminous in the emission lines and can thus be observed spectroscopically to distances of tens and even hundreds of Mpc. Emission lines have even been observed in galaxies at redshifts greater than 2 (Pettini et al. 1998). Finally, giant H II regions can be thought of as small-scale versions of the starburst phenomenon, and by studying well-resolved nearby GHRs we can learn much about star formation in starbursts and the impact of starbursts on the local environment.

A search of the ADS abstract database lists approximately 50 papers involving extragalactic H II regions by the Peimberts. Many of these studies represented pioneering efforts in the study of GHRs and chemical evolution in galaxies. In this short review I will discuss a few of the important issues and outline the Peimberts' contributions to these studies. In 1975, Manuel Peimbert wrote an article for *Annual Reviews of Astronomy and Astrophysics* on extragalactic H II regions (Peimbert 1975), which I will use as a point of comparison.

2. SPATIAL STRUCTURE OF STARS AND GAS IN EXTRAGALACTIC H II REGIONS

The classical model of an H II region is that of a spherical gas cloud illuminated by a central source of UV ionizing radiation. High resolution imaging studies of both Galactic and extragalactic H II regions with the *Hubble Space Telescope* show this to be a poor approximation. The Orion Nebula, for example is now known to be a thin ionized atmosphere on the surface of a molecular cloud (O'Dell 2001; Ferland 2001); the nebula is more like a blister than a sphere. *HST* images of GHRs (e.g., Fig. 1) show the bright central part of GHRs to be a roughly spherical cavity, with diameters of roughly 30 pc for 30 Doradus, NGC 604, and NGC 2363. This suggests that the GHR structure is analogous to that of Orion, but on a much larger scale. In many cases, such as the NW region of I Zw 18 and NGC 2363,

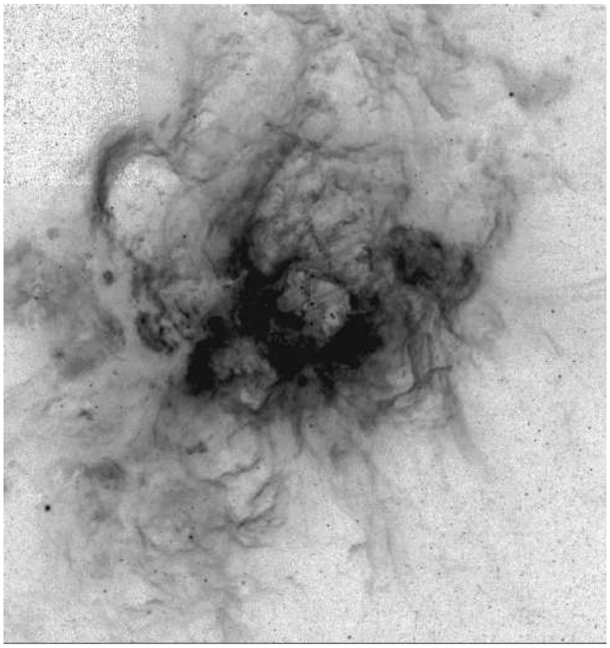

Fig. 1. WFPC-2 image of NGC 604 in M33, in the F656N filter corresponding to Hα. The image covers an area approximately 90″, or 350 pc, on a side.

a compact high surface brightness knot is seen along the rim of the shell. Very large complexes such as NGC 5471 in M101 may have several bright knots (Kennicutt 1984). The bright central structure is typically surrounded by a large halo of diffuse gas, often in the form of supershells (Fig. 1).

Massive star formation in GHRs presents some interesting puzzles. The OB associations that ionize GHRs appear to form with a variety of stellar densities. NGC 604 and the NW region of I Zw 18 have OB associations with relatively low stellar densities (Hunter & Thronson 1995; Hunter et al. 1996). In contrast, 30 Doradus contains the dense compact cluster R136 (Hunter et al. 1995). Very young, obscured star clusters are now being found in GHRs and starbursts; the most luminous clusters in NGC 5253 and NGC 2363 appear to be highly obscured sources associated with dense gas (Calzetti et al. 1997; Drissen et al. 2000). The reason why GHRs and starbursts produce OB clusters with such a wide range of densities is a fundamental mystery. High-resolution IR studies of these young obscured sources will be crucial to understanding the various modes of massive star formation in galaxies.

Wolf-Rayet stars are commonly seen in GHRs and starburst galaxies. The high W-R/O star ratios are interpreted to indicate short star formation episodes, and spectrum synthesis models for OB clusters typically indicate a sudden turn-on of W-R features at ages of about 3 Myr (Leitherer & Heckman 1995). The presence of W-R stars is thus commonly used to infer the ages of starbursts and GHRs.

3. PHYSICAL CONDITIONS IN EXTRAGALACTIC H II REGIONS

Accurate determination of physical conditions in the ionized gas (T_e, n_e, and ionization fractions) is critical to deriving element abundances. The emissivities for collisionally-excited UV/optical forbidden lines have strong exponential dependences on T_e; assuming an ad hoc value for T_e biases one toward particular values for the abundances. Accurate measurements of n_e constrains the importance of collisional *de-excitation* of forbidden lines and collisional *excitation* of He I lines. Reliable predictions of ion fractions are necessary to derive the total abundances for elements with important unobserved ions.

The Peimberts understood the importance of determining T_e values and took great pains to measure them whenever available instrumentation permitted. Prior to 1970, T_e measurements had been made for only two extragalactic GHRs, 30 Doradus and N66 in the SMC (Aller & Faulkner 1962; Wares & Aller 1968) based on a combination of photographic and photoelectric photometry, and most abundance work was confined to measuring He/H. The introduction of multichannel scanners brought a new level of precision to H II region spectrometry. In 1970, several studies (Peimbert 1970; Peimbert & Spinrad 1970; Searle & Sargent 1972) had measured T_e in NGC 604, Hubble V in NGC 6822, II Zw 40 and I Zw 18. These studies established that dwarf galaxies were deficient in heavy elements compared to spiral galaxies. It is a testimony to the careful work of all these early observers that their T_e measurements are in very good agreement with modern values from CCD spectra.

Since then, measurements of T_e for H II regions in metal-poor dwarf galaxies have become relatively routine, because they have higher T_e due to the lack of heavy elements. However, the Peimberts also pushed to measure temperatures for metal-rich H II regions as far as possible, to extend the baseline of abundance measurements into the inner disks of spiral galaxies, as illustrated in Torres-Peimbert, Peimbert, & Fierro (1989). By observing a variety of temperature diagnostic ratios for [O III], [O II], [N II], and [S II], Torres-Peimbert et al. (1989) were able to make measurements of T_e closer to the M101 nucleus than in previous studies. This achievement stood until Kinkel & Rosa (1994) measured T_e from a deep spectrum of the region Searle 5 in M101.

One important question is whether the temper-

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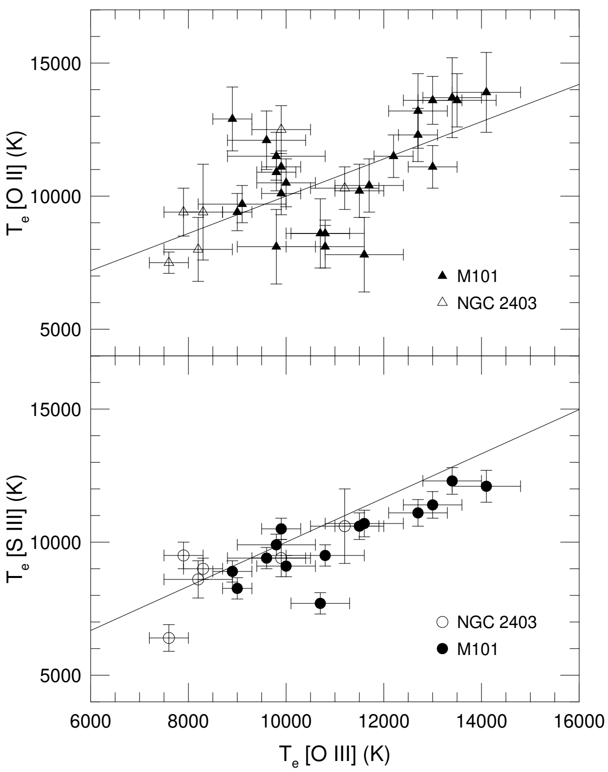

Fig. 2. Comparison of observed T[O III], T[O II], and T[S III] for H II regions in M101 and NGC 2403. The solid lines show predicted relations between the ion temperatures from photoionization models (Garnett 1992).

ature structure within H II regions is reproduced by photoionization models. This reflects the ability of simple models to predict the thermal equilibrium, which can be influenced by complex density structures or by non-thermal heating sources such as shocks. A simple comparison is to compare temperatures derived from a variety of ions which are formed in different ionization zones, such as [O III], [O II], [N II], and [S III]. All of these species provide temperature-sensitive diagnostic line ratios in the optical/near-IR spectrum, but few measurements were made until recently.

Figure 2 shows a comparison of T_e from [O III], [O II], and [S III] for $\sim$ 30 H II regions in the spiral galaxies NGC 2403 and M101 (Garnett et al. 1997; Bresolin, Kennicutt, & Garnett 2002). At present, this is the largest sample of homogeneous electron temperature measurements for any galaxy. In Figure 2 I also show the fits to the relations between T[O II], T[O III], and T[S III] derived from photoionization models by Garnett (1992). Although there is still considerable scatter in the T[O II] measurements, the resulting trend follows the predicted relation quite well. The T[S III] measurements are somewhat offset to lower temperatures from the predicted relation; this may reflect the effects of telluric absorption on measurements of the [S III] 9069 and 9532 Å lines. Given the uncertainties, the agreement between observations and theory is good.

Whenever one discusses electron temperatures in ionized nebulae, the question of temperature fluctuations lurks in the background (Peimbert 1967). Unfortunately, there are strong arguments both for and against significant temperature fluctuations (Mathis 1996). The atomic data for collision strengths and ionization/recombination cross sections are rarely known to better than 20% (Jacoby, Ferland, & Korista 2001), and so discrepancies of this order between photoionization models and observations should not be taken too seriously. Future comparisons of mid-IR and far-IR fine-structure lines with visible/near-IR transitions of the same species will likely provide the best evidence for whether or not temperature fluctuations introduce significant systematic errors in abundances in GHRs.

4. ELEMENT ABUNDANCES AND ABUNDANCE RATIOS

At the time of Manuel's ARA&A review, element abundances had been determined in only a few extragalactic H II regions outside of the Magellanic Clouds. Searle (1971) had published his survey of H II regions in spiral galaxies, and Smith (1975) was just completing his study. The first spectrophotometric surveys of Magellanic Cloud H II regions (Peimbert & Torres-Peimbert 1974; Dufour 1975; Peimbert & Torres-Peimbert 1976) were being concluded. Several noteworthy results came out of these studies: (1) Helium abundances in metal-poor H II regions were close to the solar neighborhood value (i.e., in Orion). Since metal-poor galaxies could not have processed much of their gas through stars, this demonstrated that most of the helium was the result of primordial nucleosynthesis. The Peimberts made contributions to this subject that are still used today. Peimbert & Torres-Peimbert (1974) showed that the He^+/H^+ ratio is correlated with the O^+ fraction; to minimize the uncertain contribution of neutral He, it is best to measure He in regions with very low O^+ fractions. In addition, Peimbert & Torres-Peimbert (1974), by making the simple assumption that the He mass fraction varies linearly with metallicity, were able to extrapolate the measured He mass fractions to zero metallicity, thus obtaining the pre-galactic value Y_p. This method is still applied in the most recent attempts to determine Y_p. (2) There appeared to be radial gradients in the composition of the gas

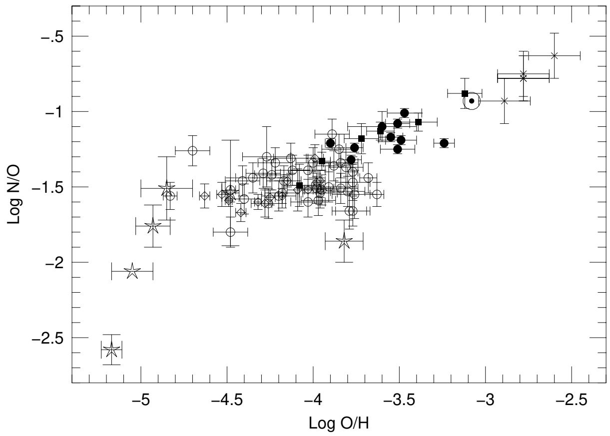

Fig. 3. Log N/O vs. log O/H in extragalactic H II regions and damped Lyman-α systems. Open circles: irregular galaxies from Garnett 1990; open diamonds: dwarf galaxies from Thuan et al. 1995; filled circles, squares, crosses: H II regions in spiral galaxies (Garnett et al. 1997; Torres-Peimbert et al. 1989; Díaz et al. 1991); stars: high-redshift damped Lyman-α systems from Lu, Sargent, & Barlow 1998. Note the very low N/O in some DLA systems.

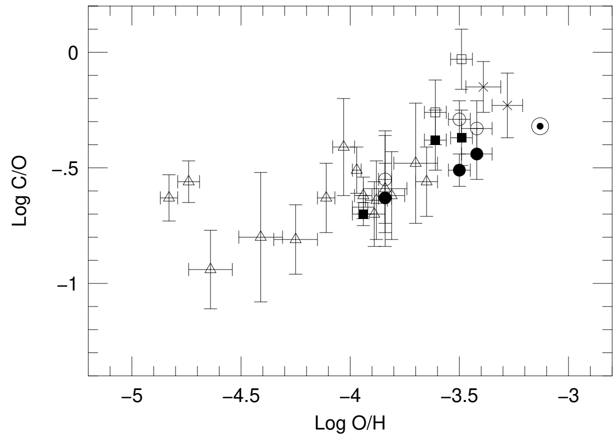

Fig. 4. Log C/O vs. log O/H in extragalactic H II regions. Open triangles: irregular galaxies from Garnett et al. 1995; open, filled circles and squares: spiral galaxies from Garnett et al. 1999.

in spiral galaxies, in the sense that the outer regions are more deficient in heavy elements. This had been hinted at by other lines of evidence such as radial variations in the ratio of red to blue supergiants, but was demonstrated definitively by observations of H II regions. (3) Nitrogen abundances appeared to more deficient than oxygen in the most metal-poor H II regions. (4) There appeared to be a correlation between the mass of a galaxy and its metallicity (see also Lequeux et al. 1979).

Much of the work on abundances in spiral and irregular galaxies during the following 20 years confirmed these results, expanding the database on abundances and abundance gradients to include some 50 spiral galaxies and more than 100 irregular galaxies. At the same time, enough data on molecular and neutral gas distributions and stellar surface brightness profiles have accumulated to study the metallicity evolution of galaxies as a function of galaxy Hubble type, mass, and surface density. It is not my intention to review these results in the context of metallicity evolution, as this will be discussed elsewhere in this volume (see also Vila-Costas & Edmunds 1992 and Garnett 1999). Instead, I will present a compilation of the data on element abundance ratios in extragalactic H II regions with high quality measurements of physical conditions.

Nitrogen: Lequeux et al. (1979) noted that the N/O abundance ratio appeared to decline as O/H decreases, but not as rapidly as would be expected if nitrogen were purely a secondary element produced from pre-existing C and O in stars via CNO cycle nucleosynthesis. They suggested that the observed nitrogen includes a component from primary nucleosynthesis, that is, N that is produced from freshly synthesized C and/or O; this component comprises a larger fraction of the total N at low metallicities. A likely source for this primary N is hot CNO-cycle burning of freshly produced C that has been convectively dredged up into the H-burning zone of asymptotic giant branch stars.

Figure 3 shows data for a variety of H II regions in spiral and irregular galaxies that nicely illustrates this primary-secondary behavior for N. For $\log \mathrm{O/H} > -3.7$, where the data come from spiral galaxies, we see N/O increasing with O/H, showing the increasing contribution from secondary nitrogen. For $-4.8 < \log \mathrm{O/H} < -3.7$, we see that N/O is essentially constant, reflecting the dominance of primary nitrogen in the low-metallicity galaxies. Measurements in a few damped Lyman-α systems at high redshifts (stars in Fig. 3) show very low N/O. These may be truly young systems, suggesting that the higher N/O in the dwarf galaxies is indeed due to primary N from AGB stars.

Carbon: In 1975, no data on carbon in extragalactic H II regions were available. It was not until the *IUE* spacecraft was launched that carbon abundances could be derived, through measurements of the C III] 1909 Å line (see Dufour, Schiffer, & Shields 1984). The launch of the *Hubble Space Telescope* improved matters, with better UV sensitivity and spec-

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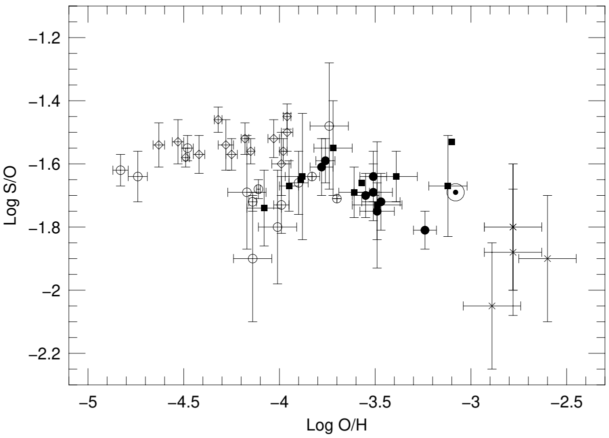

Fig. 5. Log S/O vs. log O/H in extragalactic H II regions. Open circles and squares: dwarf galaxies from Garnett (1989) and Thuan et al. (1995). Filled symbols and crosses: H II regions in spiral galaxies (Garnett et al. 1997; Torres-Peimbert et al. 1989; Díaz et al. 1991).

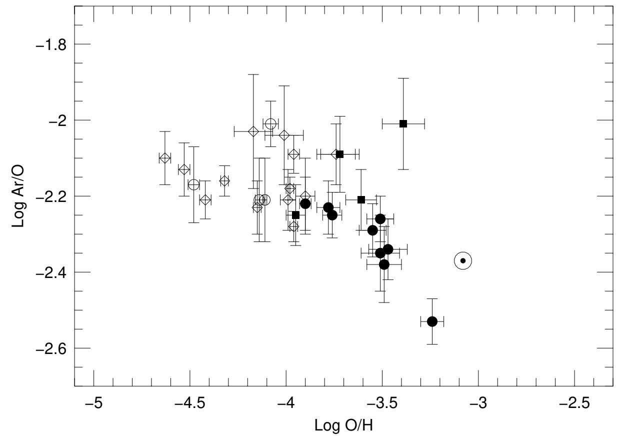

Fig. 6. Log Ar/O vs. log O/H in extragalactic H II regions. Symbols are the same as in Fig. 5.

tral resolution, and the ability to measure C/O ratios independent of ground-based spectroscopy. It has been a pleasure to collaborate with the Peimberts and my Texas colleagues on a program to measure C abundances over a wide range of metallicities in spiral and irregular galaxies. Figure 4 shows C/O vs. O/H in extragalactic H II regions from these studies (Garnett et al. 1995; Garnett et al. 1999). These data show a trend similar to that seen in nearby stars: C/O decreases with O/H from solar O/H down to about one-tenth solar O/H, flattening out below one-tenth solar O/H an average C/O value of about one-third the solar ratio.

The interpretation of these results is not completely straightforward. The yield of carbon is poorly constrained because of the large uncertainty in the $^{12}C(\alpha,\gamma)^{16}O$ reaction rate, and uncertainty in convective mixing and the effects of stellar mass loss. However, in loose terms, the trend suggests that dwarf galaxies are dominated by products of massive star nucleosynthesis, while in the more metal-rich spiral galaxies we see an increasing contribution of carbon from intermediate mass stars plus increased C production from massive stars with larger mass loss rates (Maeder 1992).

Sulfur and Argon: Sulfur and argon are mainly the products of rapid oxygen burning in the late stages of evolution of a massive star. Their yields may be sensitive to stellar interior conditions immediately prior to and during the supernova explosion, for example explosive nucleosynthesis or fallback onto the compact remnant. Nevertheless, to first order the abundances of S and Ar are expected to track the O abundance closely. Large deviations of S/O and Ar/O from the predicted, roughly solar, value may signal variations in the stellar initial mass function (IMF) or in the nucleosynthesis.

Figures 5 and 6 shows a compilation of of S/O and Ar/O measurements in extragalactic H II regions from optical spectra. Contrary to theoretical expectation, we see an apparent trend in both S/O and Ar/O toward lower values at high metallicities. The reason for this trend is not clear. It is possible that the trend is a result of uncertainties in T_e or sulfur ionization in metal-rich H II regions, where T_e is rarely measured. Increasing S/O at high O/H would require either higher T_e or a larger ionization correction for S^{+3}. Measurements of S and Ar abundances from IR lines are needed to understand the behavior of these elements at high metallicities.

5. OPEN ISSUES

There are a number of issues regarding GHRs that require further study.

(1) How does star formation proceed in GHRs? Clearly, there is more than one mode of star formation, one that produces compact massive clusters and one that produces loose associations. Determining why this occurs requires a much deeper understanding of star formation than we have at present.

(2) How do we interpret the presence of W-R stars in GHRs? The presence of W-R stars is commonly interpreted to indicate an age of 3–6 Myr. However, W-R stars are seen in the R136 cluster, which has an age < 2 Myr. Hot W-R stars are predicted to produce copious amounts of He^{+}-ionizing radiation in metal-rich regions, yet the effect of this hard ionizing radiation is absent (Bresolin, Kenni-

cutt, & Garnett 1999). Finally, it is apparent that the youngest stellar populations in GHRs may be highly obscured even in metal-poor galaxies. Thus it appears that we do not completely understand the role of W-R stars in starbursts.

(3) What is the impact of the OB stars on the environment? Do ionizing photons escape GHRs in sufficient numbers to ionize the diffuse ionized gas? Do metals escape from GHRs into the galaxy halo?

(4) What are the abundances in H II regions in the inner disks of spirals? These are not known with great accuracy because of the lack of T_e measurements. Chemical evolution models for spirals typically predict that the metallicity gradients flatten in the inner disk. There is no evidence for this at present in the data, but the abundances are poorly constrained. Measurements of IR fine-structure lines for these regions are needed to understand the chemical evolution of the inner regions of spirals.

It has been a great pleasure to interact with the Peimberts scientifically and socially over the past 15 years, from the time I was a clueless graduate student at Texas. I am sorry that illness forced me to cancel my attendance at this conference in their honor. I look forward to working with them for many more years to understand the problems of ionized nebulae.

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D. R. Garnett: Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ, 85721, USA (dgarnett@as.arizona.edu).

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