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The CHAOS Survey

Danielle A. Berg[1], Richard W. Pogge[1], Evan D. Skillman[2], Kevin V. Croxall[3], John Moustakas[4] and Ness Mayker[1]

[1]Dept. of Astronomy, The Ohio State University, 140 W 18th Ave., Columbus, OH, 43210
[2]Institute for Astrophysics, University of Minnesota, 116 Church St., Minneapolis, MN 55455
[3]Illumination Works LLC, 5650 Blazer Parkway, Suite 152, Dublin OH 43017
[4]Dept. of Physics & Astronomy, Siena College, 515 Loudon Road, Loudonville, NY 12211

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1. Introduction

Our very best understanding of the abundances in spiral galaxies comes from detailed spectroscopic studies and measurements of their faint, sensitive emission lines using either temperature-sensitive auroral collisionally-excited lines (CELs) or recombination lines (RLs). However, the RL method is known to produce systematically higher oxygen abundance measurements than the CEL-method (e.g., García-rojas & Esteban 2007), and which method is more accurate is still debated in the astronomical community. Because of the inherent faintness of both the auroral CELs ($\sim 10^2\times$ fainter than Hβ) and the RLs ($\sim 10^3\times$ fainter than Hβ), extragalactic abundance measurements are commonly based on empirical calibrations to stronger emission lines or photoionization modeling. Unfortunately, these so-called strong-line calibrations, which are the typical method of determining galactic abundances in lower S/N spectra, including IFU surveys and high redshift targets, demonstrate large systematic discrepancies amongst different methods (Kewley & Ellison 2008). Thus, all ISM abundances derived from emission-line spectra, especially those based on strong-line calibrations, are fundamentally limited by the current lack of an accurate absolute abundance scale.

The CHemical Abundances of Spirals (CHAOS) survey leverages the combined power of the dual 8.4m mirrors on the Large Binocular Telescope (LBT) with the broad spectral range (3400Å $< \lambda < 1\mu$m) and sensitivity of the Multi Object Double Spectrograph (MODS; Pogge *et al.* 2010) to measure the physical conditions and abundance gradients of nearby spiral galaxies. With a field of view comparable to the angular diameters of the nearest spiral galaxies, we have used laser-machined slit masks to obtain multi-object spectroscopy of ~ 650 H II regions across 11 face-on spiral galaxies. To date, 5 galaxies have been analyzed with an unprecedented number of temperature-sensitive auroral CEL detections: NGC 628 (46 regions; Berg *et al.* 2015), NGC 5194 (30 regions; Croxall *et al.* 2015), NGC 5457 (75 regions; Croxall *et al.* 2016), NGC 3184 (32 regions; in prep), and M 33 (in prep).

2. First Results from CHAOS

CHAOS has produced the richest data set to date of direct elemental abundances of HII regions in nearby bright spiral galaxies derived from electron temperature (T_e) measurements. In Berg *et al.* (2015) we observed significant auroral line detections from one or more ions in 47 HII regions across the disk of our first CHAOS target, NGC 628, amassing an unprecedented total of 126 individual auroral line measurements within a single galaxy. Comparing derived temperatures from these auroral line measurements revealed some surprising results. While the [OIII] λ4363/($\lambda\lambda$4959,5007) auroral-to-strong-line ratio has long been the principle nebular temperature diagnostic, we found large discrepancies for temperatures based on [OIII] λ4363. Yet, temperatures based on [SIII] λ6312 and [NII] λ5755 showed a very tight relationship, indicating that these temperatures are reliable. Further, the dispersion in the O/H gradients in our sample is minimized when prioritizing abundances based on T_e[SIII] and T_e[NII] over T_e[OIII].

The CHAOS $T_e - T_e$ results have been confirmed in additional targets: NGC 5194 (Croxall *et al.* 2015), NGC 5457 (Croxall *et al.* 2016), and NGC 3184 (Berg *et al.*, in prep). This CHAOS dataset reveals offsets from the commonly used $T_e - T_e$ relationships predicted by photoionization modeling (e.g., Garnett et al. 1992). In Croxall *et al.* (2016) we provide updated $T_e - T_e$ relationships that are empirically calibrated using T_e detections from 74 HII regions in NGC 5457. These data also allowed us to robustly measure the physical conditions in a significant number of low-ionization HII regions, and propose new empirical ionization correction factors for S and Ar.

3. Next Steps: True Chemical Abundances of Spiral Galaxies

While the unprecedented number of auroral line detections in the CHAOS dataset has led us to breakthroughs in our understanding of HII region abundance determinations, further progress requires additional avenues of investigation. First, we have been able to measure the *Balmer Jump* in the nebular continuum near λ3650 in a significant number of CHAOS spectra (CHAOS team, in prep.). This provides an estimate of the mean T_e in an HII region derived independently from the CEL temperatures, allowing us to evaluate the importance of fluctuations within the regions (c.f., Guseva *et al.* 2006, 2007). A second measure of temperature inhomogeneities comes from the handful of CII RL measurements observed in each of two CHAOS galaxies to date (M101 and M33; Skillman et al., in prep.). Because RLs are far less sensitive to the T_e (linear dependence) than CELs (exponential dependence), temperature fluctuations have been proposed as the source of the discrepancies in abundances derived from the two methods (e.g., Peimbert 1969). Follow-up UV spectra will be obtained for these regions in M101 using the Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope (*HST*) in Cycle 26 (HST-GO-15126; PI: Berg). The OIII] $\lambda\lambda$1661,1666 and CIII] $\lambda\lambda$1907,1909 CELs will be measured from these spectra, allowing the most accurately measured carbon abundance gradient in a spiral galaxy to date. Many of the HII regions in our sample have also been observed in the mid-IR with Spitzer or Herschel. These spectra allow us to compare abundances from the temperature-insensitive fine-structure IR emission lines to our CHAOS abundance for a third measure of temperature fluctuations (e.g., Garnett *et al.* 2004; Croxall *et al.* 2013).

Finally, we can measure present-day abundances from blue super giant (BSG) stars, which recently formed from and have the same chemical composition as the gas in their surrounding HII regions, as standards for the absolute abundance scale. The extreme brightness of BSGs makes it possible to obtain resolved spectra of individual BSGs out to 10 Mpc with current instrumentation. From the CHAOS sample, 10 galaxies are within this 10 Mpc distance necessary to accurately measure abundance from BSGs. BSG abundance gradients have been measured for several nearby spiral galaxies, including NGC 300 (Kudritzki *et al.* 2008), NGC 3031 (Kudritzki *et al.* 2012), and M83 (Bresolin *et al.* 2016). Spectroscopic observations of BCGs and/or HII regions are planned for the CHAOS sample, from which we will compare CHAOS nebular abundances with the BSG abundances as a function of radius from each galaxy's center. This will allow us to further resolve the CEL/RL abundance discrepancy problem and better anchor the strong-line calibrations.

4. Summary

The CHAOS survey has measured high-quality optical spectra in 100s of HII regions across 11 nearby spiral galaxies. This dataset represents the most accurate and precise study of direct CEL abundances across a broad range of physical conditions in extra-galactic HII regions to date, and so provides a rich database from which an absolute nebular abundance scale can be calibrated.

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