A Metallicity Map of M33

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Abstract. We present initial results from the M33 Metallicity Project. Out of the thousands of cataloged H II regions in M33, only $\sim 30$ have electron-temperature based abundances in the literature. We have obtained Keck spectroscopy of a sample of $\sim 200$ H II regions in M33, with 61 detections of the [O III] $\lambda$4363 Å line that can be used for determining electron temperatures, including measurements at small galactocentric radii where auroral lines are generally difficult to detect. We find an oxygen abundance gradient of $-0.027 \pm 0.012$ dex kpc$^{-1}$, in agreement with infrared measurements of the neon abundance gradient but much shallower than most previous oxygen gradient measurements. There is substantial intrinsic scatter of 0.11 dex in the metallicity at any given radius in M33, which imposes a fundamental limit on the accuracy of gradient measurements that rely on small samples of objects. Finally, we present a two-dimensional map of oxygen abundances across the southern half of M33 and discuss the evidence for deviations from axisymmetry.

1. Introduction

Despite decades of observations of the chemical abundances of stars, H II regions, and planetary nebulae, the chemical evolution of galaxies is still a relatively data-starved subject. Among disk galaxies (excluding the Milky Way where our location makes it difficult to discern the global structure), the best studied objects are M101 (25 H II region abundances; Kennicutt, Bresolin, & Garnett 2003) and M33 (32 H II region abundances; Vílchez et al. 1988, Crockett et al. 2006, Magrini et al. 2007). In both of these galaxies, the existing metallicity measurements have a spatial sampling rate of $\lesssim 0.2$ kpc$^{-2}$. Since H II regions and supernova explosions typically affect volumes that are less than a few hundred pc in radius, these data are too sparsely sampled to reveal how chemical enrichment has proceeded. In particular, the mixing of metals through the interstellar medium (ISM) is not yet very well constrained observationally (e.g., Scalo & Elmegreen 2004, and references therein), and whether the spatial distribution of heavy elements is more complex than the typically assumed simple exponential gradient with radius is completely unknown. An additional problem in the study of extragalactic abundances is the systematic differences between the two main techniques for measuring abundances: the so-called “direct” methods in which the electron temperature is measured directly using auroral line fluxes, and the empirically calibrated strong-line methods that use the flux ra-

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tions of bright emission lines as a proxy for the oxygen abundance. Motivated by these considerations, we have undertaken the M33 Metallicity Project — a long term effort to obtain Keck/LRIS spectroscopy of a sample of $>500$ H ii regions in M33 that will provide an unprecedentedly large database of uniformly determined oxygen, nitrogen, and sulfur abundances in an external galaxy.

2. Data and Results

Using the LRIS spectrograph (Oke et al. 1995) on the Keck I telescope, we have observed over 200 H ii regions in M33. Details of the observations, data reduction, and analysis are given in Rosolowsky & Simon (2007, hereafter RS07). We detected the [O iii] $\lambda$4363 Å line and therefore derived direct oxygen abundances in 61 of the H ii regions, approximately tripling the sample of M33 metallicity measurements available in the literature.

We display our new abundance measurements as a function of radius in Figure 1a. A weak gradient is visible, but the intrinsic scatter in the data (which is significantly larger than the observational uncertainties) dominates the plot. We therefore must use the method described by Akritas & Bershady (1996) to determine the gradient. We measure an oxygen abundance gradient of $-0.027 \pm 0.012$ dex kpc$^{-1}$, shallower than all previous gradient measurements except that of Crockett et al. (2006, hereafter C06), and the intrinsic scatter in the metallicities at any given radius is 0.11 dex (RS07).

3. Discussion

The oxygen abundance gradient that we measure is in good agreement with infrared measurements of the neon abundance gradient by Willner & Nelson-Patel (2002), who found a slope of $-0.034 \pm 0.015$ dex kpc$^{-1}$. However, our new determination does not appear consistent with most previous optical studies of the abundance gradient in M33, which generally found steeper slopes. Why does our gradient measurement disagree with these other studies? For the objects in our sample that have abundance measurements in the literature, our oxygen abundances agree within the uncertainties (see RS07), indicating that systematic errors and sample selection biases are probably not to blame. Since we primarily observed H ii regions in the southern half of the galaxy, and most previous studies focused on the northern side, it is possible that a highly asymmetric abundance distribution could account for the discrepant results, but this hypothesis can only be tested with additional observations.

We are therefore left with two possible explanations. The first is that Vílchez et al. (1988, hereafter V88), the largest of the earlier studies, relied on photoionization modeling for the abundance of one H ii region near the center of M33. The high derived abundance for this object significantly steepened the overall gradient they derived to $-0.10$ dex kpc$^{-1}$ (after rescaling to our assumed distance); as V88 noted, the gradient of the outer H ii regions in their sample is only $-0.05 \pm 0.01$ dex kpc$^{-1}$, much closer to more recent measurements. This difference suggests that the photoionization model abundances may be systematically higher than direct abundances. Second, the significant intrinsic scatter in the abundances revealed by our larger sample prevents measurements based
Figure 1. (a) Oxygen abundance gradient in M33. A linear gradient with a slope of $-0.027$ dex kpc$^{-1}$ is fit to the data (solid line). Regions with significant He II $\lambda 4686$ Å emission are indicated with open symbols. The dashed and dotted lines represent the gradients measured by Crockett et al. (2006) and Vilchez et al. (1988), respectively. The data are not consistent with the steep slopes of $\sim -0.1$ dex kpc$^{-1}$ found by the original M33 studies. (b) Monte Carlo simulation showing the distribution of the abundance gradients that would be measured for a sample of 10 H II regions drawn randomly from our sample of 61. The large width of distribution shows the uncertainty imprinted upon the abundance determinations by the underlying variance. The measurements of Vilchez et al. (1988) and Crockett et al. (2006) are indicated and are consistent with the distribution given their small sample sizes.

We plot in Figure 1b the outcome of a Monte Carlo simulation in which we measured the abundance gradient in M33 by randomly selecting 10 H II regions out of our full sample of 61 many times. The broad width of the resulting distribution demonstrates that significantly larger samples are needed in order to derive accurate results. Even with 61 oxygen abundances, we only detect the gradient at 2.3 $\sigma$ significance! Although our measured gradient is formally outside the 1 $\sigma$ uncertainties of the gradient slopes reported by V88, C06, and Magrini et al. (2007), when the intrinsic scatter and small sample sizes are taken into account their results are consistent with our data (see Figure 1b).

In Figure 2 we display the two-dimensional metallicity distribution we have derived for M33 overlaid on an H$\alpha$ image of the galaxy. As can also be seen in Figure 1a, the highest metallicity H II regions are not located at the center of the galaxy, but rather lie along the southern spiral arm at a radius of 1–2 kpc. This distribution suggests that the material enriched by the most recent generation of star formation in the arm has not yet been azimuthally mixed through the galaxy. These data represent some of the first evidence for a non-axisymmetric abundance distribution in the interstellar medium of M33. As we build up a larger data set and cover the northern side of the galaxy, these measurements will allow us to constrain the mixing timescale and better understand the processes by which heavy elements are transported through the galaxy.
Figure 2. Metallicity map of the southwest half of M33. The white circles show the locations of our oxygen abundance measurements, and the solid black contours represent metallicity. The dotted ellipses are curves of constant galactocentric radius (spaced at 1 kpc intervals), and the center of the galaxy is marked in the upper left with an “X”. The highest metallicities occur not at the center of M33, but in the southern spiral arm.

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