Part 4. Detailed Chemical Abundances

Section A. Invited Reviews

During the DAO tour Monica Rubio, Ray Haynes and You-Hua Chu examine receiver technology developed for the James Clerk Maxwell Telescope (top), while David Crampton and William Rambold demonstrate components of the Gemini Multi-Object Spectrographs.

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Stellar Metallicities in the Magellanic Clouds

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Abstract. The overall stellar metallicity scale as a function of age for both Magellanic Clouds reveals that they have followed a different pattern of enrichment when compared to each other as well as to the Galactic disk. In addition, an investigation into the abundances of two key elements, oxygen and europium, shows that the detailed nucleosynthesis history of these systems is unique in comparison to any Galactic population yet studied.

1. Introduction

The Large and Small Magellanic Clouds (LMC and SMC) are distinct stellar environments in comparison to the Galactic disk, halo, or the globular cluster system. In this brief review, we concentrate on two aspects of stellar abundances in the Clouds: 1) the age-metallicity trends for both the LMC and SMC, and 2) the abundance patterns of oxygen, the r-process elements and, in particular, the representative r-process element europium. These results provide insight into chemical evolution in systems quite different from the Milky Way.

2. Age-Metallicity Relations

Age-metallicity relations are fundamental properties which define the overall chemical evolution and enrichment in stellar systems. When combining data on age and metallicity in samples from the LMC and SMC, it is found that the Clouds seem to exhibit distinct histories, both in comparison to each other and to our Galaxy. Olszewski et al. (1991) and Dopita (1996) provide extensive results for LMC ages and metallicities. (Dopita's results are from planetary nebulae, while Olszewski et al. studied clusters). These studies can be supplemented by the recent results from Geisler et al. (1997) and Bica et al. (1998) for LMC clusters, who find generally similar trends. For the SMC, the most recent studies are from Da Costa & Hatzidimitriou (1998), who also analyzed clusters. Figure 1 shows a summary of ages and metallicities for the LMC and SMC, along with work from Edvardsson et al. (1993) on the Galactic disk stars. Note that for the Galactic disk we plot directly the Fe abundances, while the cluster work in both of the Clouds is based upon low-resolution spectroscopy of the Ca II

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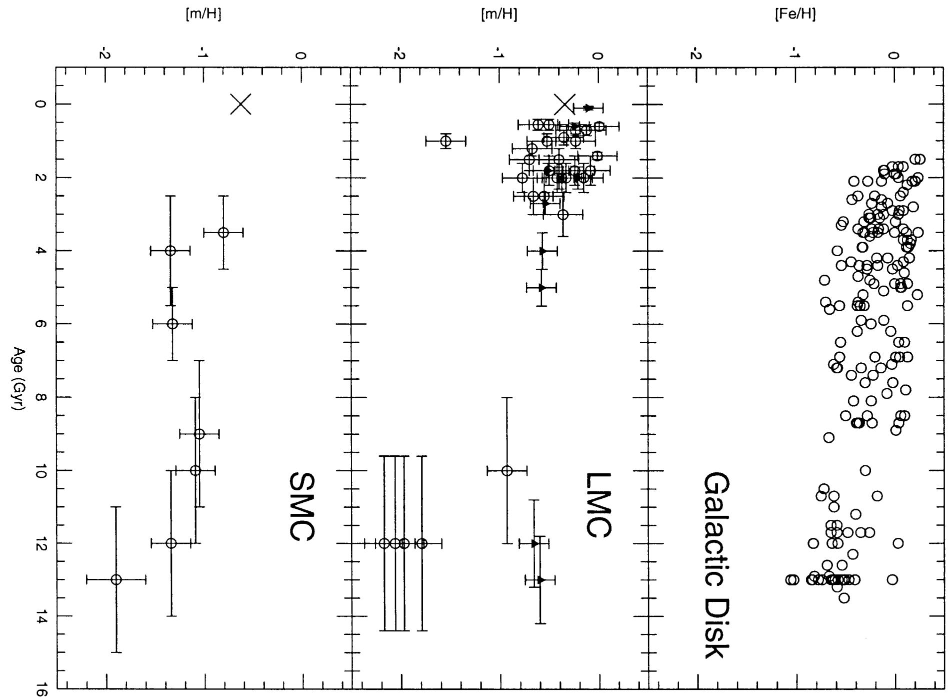

Figure 1. Age-metallicity relations for three systems. The Galactic disk data are from Edvardsson et al. (1993), while the SMC data are from clusters studied by Da Costa & Hatzidimitriou (1998). The LMC results also contain cluster work from Olszewski et al. (1991 - open circles) and Dopita (1996 - filled triangles), who studied planetary nebulae.

IR-triplet, which is calibrated to the Fe abundances of well-studied open and globular clusters (we label this [m/H]). The Dopita results are for mostly lighter alpha-elements.

The current abundances for the LMC and SMC are shown in Figure 1 represented by the large X's; these values have been culled from a number of sources in the literature, all for the youngest populations (with ages of less than 5×10^8 yr). For the LMC we have used Luck et al. (1998), Spite, Barbuy, & Spite (1993), Russell & Dopita (1992), and Richtler, Spite, & Spite (1989). For the SMC we used Luck et al. (1998), Plez, Smith, & Lambert (1993), Russell & Dopita (1992), and Spite, Spite, & Francois (1989). The average values for the current [Fe/H] values are -0.30 for the LMC and -0.62 for the SMC.

The age-metallicity relations for the three systems in Figure 1 exhibit different behaviors. The Disk abundances rise slowly but steadily from an initial [Fe/H]~ -1 towards a current [Fe/H] ~ 0, but with a fair amount of scatter at all ages (perhaps ± 0.3 dex). The SMC also exhibits a slow and steady increase

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from [m/H]= −2 to a current value of about −0.6. The LMC, on the other hand, shows a very rapid rise in metallicity at a time of about 12 Gyr ago (from [m/H] = −2 to −1), then an almost constant value until 2 Gyr ago, when the metallicity increased from −1 to its current value of ~ −0.3. Note the apparent lack of intermediate-age clusters in the LMC, which may be related to the almost constant metallicity over this time period. Recently, Geisler et al. (1997) confirmed this gap in a more detailed survey.

3. Abundance Patterns

In the previous section we illustrated the general behavior of the buildup of metallicity in the Clouds over time. It is clear from the age-metallicity relations in Figure 1 that chemical enrichment in the Clouds has followed a different pattern than in the Galactic disk. Here we discuss the behavior of the abundances of two elements that show that the Clouds have not only undergone a different overall rate of chemical enrichment, but that the details in the abundance distributions are also different. We choose to discuss oxygen and the heavy, neutron-rich elements.

Using the references cited in Section 2, which are used to define the current metallicity, we can also define the current oxygen abundances in the Clouds: [O/Fe] for the LMC is about −0.2 and about −0.1 for the SMC. At the respective values of [Fe/H] for each Cloud, the Galactic disk values of [O/Fe] are +0.0 (at the LMC [Fe/H]) and +0.2 (at the SMC [Fe/H]). Thus, both Clouds seem to be deficient in O, relative to Fe, by about 0.2-0.3 dex in comparison to the Galactic disk. These abundances are taken from a number of studies, suggesting that this is a real effect. Oxygen is made preferentially in the most massive stars, while Fe comes from both massive, core-collapse supernovae (SN II) and the (presumably) binary SN Ia's. It is possible that in small systems, such as the Clouds, very massive stars are formed in a few starbursts (over the age of the galaxy), while lower mass stars (such as the members of the presumed binary progenitors of the SN Ia's) are formed more continuously and thus eject Fe at a more constant rate, leading to a decreased O/Fe ratio.

Another peculiar chemical signature in the LMC and SMC is found in an examination of the heavy, neutron-rich elements produced by neutron-capture nucleosynthesis. These nuclei are separated into two fairly distinct families consisting of isotopes produced by very slow neutron captures (where successive neutron captures for a given nucleus are separated by months to years - the s-process), and those isotopes produced by extremely rapid neutron captures (where dozens of successive neutron captures occur on a timescale of a few seconds - the r-process). The s-process elements are dominated by production in low- to intermediate-mass asymptotic giant branch (AGB) stars, while the r-process is believed to occur during events associated with the core collapse of a SN II. All of the various studies mentioned in Section 2 tend to find that the Clouds are somewhat overabundant in the heavy elements, relative to Fe. The overabundance pattern is characteristic of the r-process and not the s-process: this aspect of the pattern was emphasized by Plez, Smith, & Lambert (1993). In Figure 2 are summarized the abundances of the heavy elements (heavier than Sr), as tabulated by Luck et al. (1998) and Russell & Dopita (1992), for both

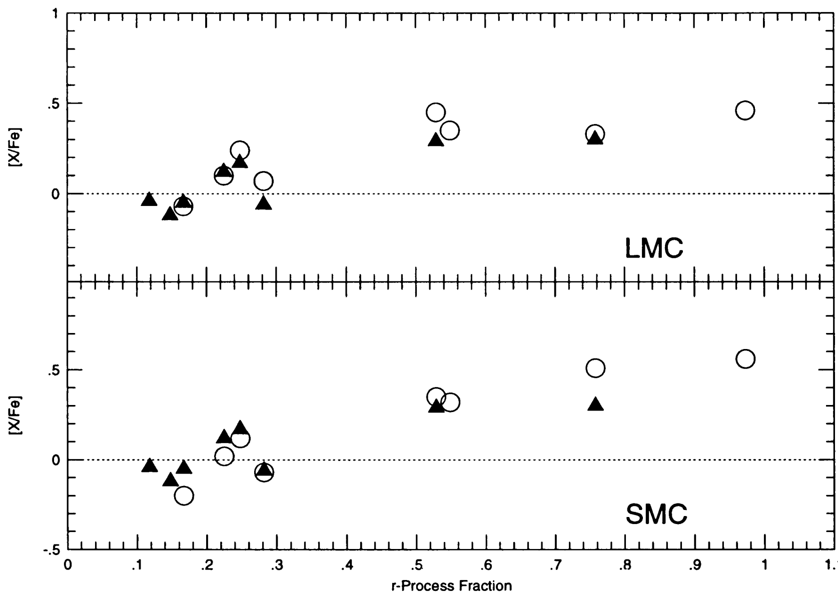

Figure 2. Heavy-element abundance ratios versus the r-process fraction for elements heavier than Sr. The open circles are from Luck et al. (1998), while the filled triangles are from Russell & Dopita (1992). The Cloud heavy-element abundances are dominated by an r-process component.

Clouds (these are the most complete and extensive studies of the heavy elements). We plot values of [X/Fe] versus the fraction of the element produced by the r-process (in the standard solar system abundance distribution), with these r-process fractions taken from Sneden et al. (1996). The trend in Figure 2 is obvious: the larger the r-process contribution, the more overabundant a particular element is in the Clouds. Heavy-element enrichment in the LMC and SMC has been dominated by the r-process when compared to the Galactic disk.

The chemical evolutionary implications of Figure 2 are not yet clear; recall from our earlier discussion of oxygen that the Clouds appear to be deficient in O/Fe. Figure 2 indicates that, contrary to the oxygen underabundance, the r-process is overabundant, yet both O and the r-process are believed to be created as a result of massive star evolution. The Magellanic Clouds are providing another piece of evidence that, to some degree, the production of oxygen and the r-process is decoupled.

The quintessential r-process element is europium, with an r-fraction of 0.97 (note the results for Eu in the top and bottom panels of Figure 2 with the largest values of r-fraction). In Figure 3 we summarize abundance results for Eu in various populations and plot [Eu/Fe] versus [Fe/H]. Europium is used as a proxy for the r-process component in these stellar populations. The open squares in Figure 3 represent the field halo stars (see references in the r-process section by Sneden in Wallerstein et al. 1997), which show a rather tight distribution of increasing [Eu/Fe] with decreasing metallicity, from [Fe/H]= +0.2 down to

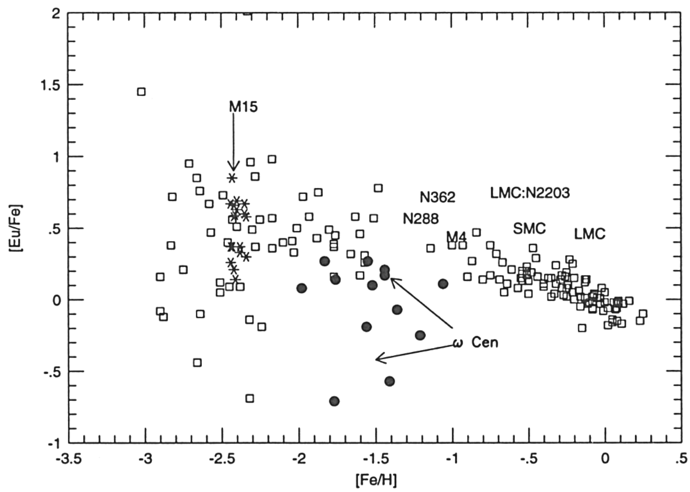

Figure 3. [Eu/Fe] as a function of [Fe/H] for various samples of stars. Open squares are Galactic field and halo stars, the six-pointed stars are from the globular cluster M15, the filled circles are from ω Cen, while the globular clusters M4 and NGC288 and NGC362 are labeled. The current LMC and SMC values are labeled, along with the LMC cluster NGC2203.

-1.0. As [Fe/H] decreases past -1.5, the scatter in [Eu/Fe] increases, becoming enormous at very low metallicities. This scatter is real and reflects differing amounts of r-process material at a given Fe abundance. Superimposed on this field star pattern, we present the results for the mono-metallicity globular cluster M15 ([Fe/H]= -2.4) from Sneden et al. (1997), which show significant scatter in [Eu/Fe]. Results for the luminous globular cluster ω Cen (Smith, Cunha, & Lambert 1995; Smith et al. 1999) are shown and stand out both for their scatter in Eu and Fe and for occupying a part of the diagram characterized by low [Eu/Fe] (relative to field stars within the [Fe/H] range of ω Cen). We also show results from Smith & Suntzeff (1999) for the globular clusters M4, NGC288 and NGC362. The current LMC value is indicated by the LMC label and we also label the current value of [Eu/Fe] for the SMC. In addition, the somewhat metal-poor LMC cluster NGC2203 is shown (Smith & Suntzeff 1999). Note how both Clouds fall above the other samples in [Eu/Fe] at a given [Fe/H]. The admittedly limited range in [Fe/H] spanned by the current LMC value and that for NGC2203 suggests that the high r-process component in the LMC has persisted over at least part of its evolution. A final conclusion from Figure 3 is not clear, but certainly points towards a qualitatively different type of chemical evolution occurring in the Clouds, especially in comparison to a system such as ω Cen.

4. Conclusions

The age-metallicity relations of the LMC and SMC indicate that chemical enrichment has followed different rates and behaviors in both Clouds: the LMC experienced a rapid enrichment more than 10 Gyr ago, followed by apparent chemical quiescence until about 2 Gyr ago, when another enrichment phase (still going on) occurred. The SMC has undergone a slower, but steadier, chemical enrichment. The current abundance of oxygen in both Clouds reveals them to be underabundant in O, relative to Fe, when compared to the Galactic disk (by about 0.2-0.3 dex). The r-process abundances, however, are strongly overabundant, relative to Fe, in the LMC and SMC. These abundances tell us that the chemical history of the Clouds is quite distinct from known Galactic populations.

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References

Bica, E., Geisler, D., Dottori, H., Claria, J. J., Piatti, A. E., & Santos, J. F. C., Jr. 1998, AJ, 116, 723

Da Costa, G. S., & Hatzidimitriou, D. 1998, AJ, 115, 1934

Dopita, M. A. 1996, in *The Sun and Beyond*, H. C. Trung & S. Vauclair, Ed. Frontieres: Gif-sur-Yvette

Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101

Geisler, D., Bica, E., Dottori, H., Claria, J. J., Piatti, A. E., & Santos, J. F. C., Jr. 1997, AJ, 114, 1920

Luck, R. E., Moffett, T. J., Barnes, T. G., III, & Gieren, W. P. 1998, AJ, 115, 605

Olszewski, E. W., Schommer, R. A., Suntzeff, N. B., & Harris, H. C. 1991, AJ, 101, 515

Plez, B., Smith, V. V., & Lambert, D. L. 1993, ApJ, 418, 812

Richtler, T., Spite, M., & Spite, F. 1989, A&A, 225, 351

Russell, S. C., & Dopita, M. A. 1992, ApJ, 384, 508

Smith, V. V., Cunha, K., & Lambert, D. L. 1995, AJ, 110, 2827

Smith, V. V., & Suntzeff, N. B. 1999, in preparation

Smith, V. V., Cunha, K., Suntzeff, N. B., & Lambert, D. L. 1999, in preparation

Sneden, C., McWilliam, A., Preston, G. W., Cowan, J. J., Burris, D., & Armosky, B. J. 1996, ApJ, 467, 819

Sneden, C., Kraft, R. P., Shetrone, M. D., Smith, G. H., Langer, G. E., & Prosser, C. F. 1997, AJ, 114, 1964

Spite, F., Spite, M., & Francois, P. 1989, A&A, 210, 25

Spite, F., Barbuy, B., & Spite, M. 1993, A&A, 272, 116

Wallerstein, G., et al. 1997, Rev.Mod.Phys., 69, 995

Discussion

Sidney van den Bergh: How is one to reconcile the apparent difference between the r- and s-process yields in the LMC, SMC and Galaxy with the apparent universality of the luminosity function of star formation reported by Phil Massey this morning?

Smith: I don't have an answer to this question but just point out that we do not understand completely how mass is returned to the ISM as a function of stellar mass.

Michael Dopita: I think that we need to worry that with the lower mass of the Magellanic Clouds we may have lost a good deal of the α-process elements through galactic winds. This would be consistent with the lower yields that chemical evolution models require for these systems.

Smith: Yes, there may be selective loss of elements depending upon the velocity of the mass ejection.

Norbert Langer: I agee that one has to worry about certain elements getting selectively expelled from dwarf galaxies. However, I think this could actually explain the high s/r - ratio in ω Centauri, since the s-process elements are ejected by stars with only few km s^{-1} while the r-process stuff is released by supernovae. It may be hard to explain the low s/r-ratio or the high r/s-rate in the MCs this way.

Smith: I agree with you on these comments.

Dominik Bomans: One point not touched upon is the mixing of elements in the Clouds. Do the data give new insights in how well mixed the MCs are?

Smith: The spectroscopic results that I have reviewed suggest that the current gas in both Clouds is well-mixed. The dispersion in current abundances is $\lesssim 0.2$ dex.

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