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The G Dwarf Problem in Messier 31

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Abstract

Fifteen WFPC2 fields sampling the volume of M31 were reduced to color magnitude diagrams. The bright giants in these CMDs were converted to abundance distributions under the assumption of fairly old age. The abundance distributions were weighted by light and used to derive an abundance distribution for the entire galaxy. This abundance distribution matches that of the solar cylinder closely, and we conclude that closed-box M31 probably suffers a G-dwarf problem more severe than that of the closed-box Milky Way.

1.1 Introduction

The G Dwarf problem is the antique name for the fact that the simplest of analytic chemical evolution models fails to match the abundance distribution of local stars in that the model predicts more stars around a tenth of solar than are observed (van den Bergh 1962). This Simple model assumes a constant yield of heavy elements from supernovae. Finite stellar lifetimes are neglected, mixing is instantaneous, and no gas is allowed in or out of the single zone. Its advantage is simplicity. If the constant yield is p and the gas-to-total mass ratio is μ, then the present-day gas metallicity is $Z = p \ln\frac{1}{\mu}$.

In comparison with the stars near our location in the Milky Way disk, we might expect this model to fail for the reason that gas is free to enter and leave. Indeed, if infall and outflow are allowed as modifications to the Simple model, then a fit to the local data is readily found (e.g. Pagel 1997, chapter 8).

In what environment might a closed-box approximation be appropriate? Perhaps a large galaxy, taken as a whole, whose deep potential will presumably have trapped most of the gas out of which it was formed. The Milky Way and M31 dominate the mass of the local group. Attempts to construct an abundance distribution for the Milky Way are rather uncertain, though it has been tried (e.g. Worthey, Dorman, & Jones 1996). In the HST era, however, M31 presents itself as a more logical target. It is twice the mass of the Milky Way, and its present day gas fraction is around 2% (van den Bergh 2000). Furthermore, HST can resolve individual red giants with modest photometric error impressively far toward the nucleus. These color-magnitude diagrams (CMDs) can be turned into abundance distributions if most of the stars are old because of the steep relationship between color and abundance in red giant stars (Grillmair et al. 1996).

Our intent in this poster is to apply the Grillmair et al. methodology to many fields within

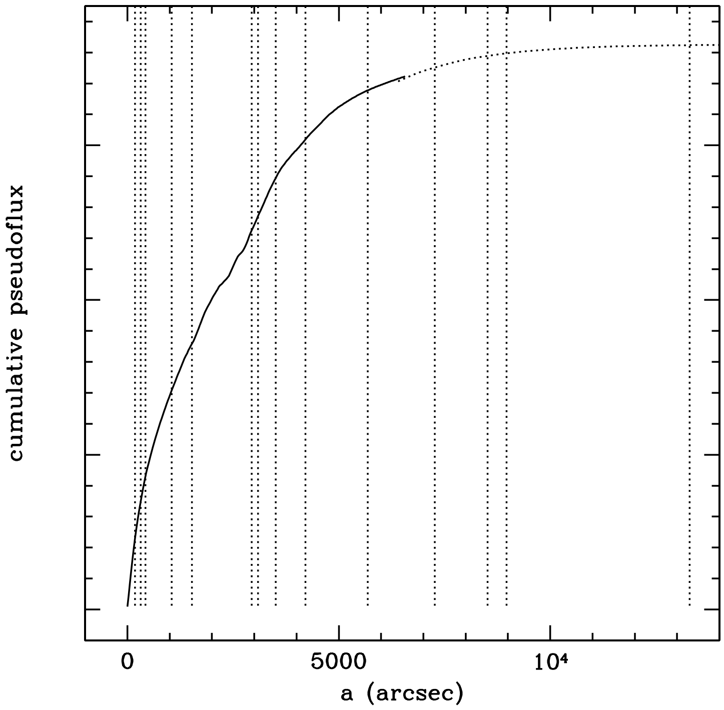

Fig. 1.1. The placements of HST fields as a function of elliptical isophotal semimajor axis are shown as dotted vertical lines, along with a cumulative light profile. For $a > 6570$ arcsec, the profile is an extrapolation based on a bulge-disk decomposition with an exponential disk.

M31, from bulge to disk to halo. We do not attempt any detailed modeling, but synthesize the global abundance distribution of the entire galaxy.

1.2 Procedure

Fields from archival HST/WFPC2 pointings in and around M31 were obtained. The various pointings sample the light of M31 fairly well (Figure 1). The images were either stacked or drizzled, as appropriate. DAOPHOT II was used for crowded-field photometry of all the fields. In the inner part of the galaxy, only the planetary camera frames were reduced, otherwise all chips were used. The resultant raw CMDs were corrected for charge transfer effects, aperture corrected, photometrically transformed to Cousins VI, and dereddened.

For the purposes of this poster a uniform age of 10 Gyr was assumed for the underlying stellar population. We echo Grillmair et al. in emphasizing that a 3/2 law operates for the temperatures of red giant branch stars: a factor of 2 change in abundance can be nullified by a factor of 3 age change in the opposite direction (Worthey 1994). For example, if a CMD looks like an old giant branch of approximately solar composition, it will lie at about the same color if it were +0.3 dex metal enhanced and 1/3 the age, say 4 Gyr instead of 12. Since it is unlikely that M31 formed in bulk so recently, more than half of the giants we see are probably quite ancient. This is bolstered by the observation of RR Lyrae stars in the halo

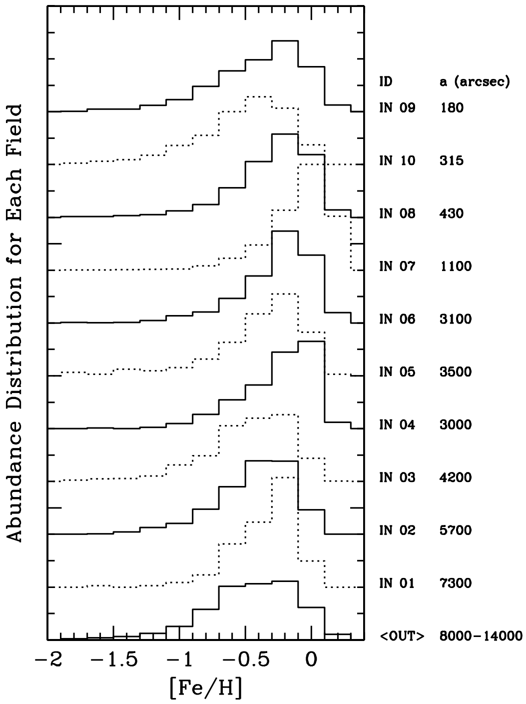

Fig. 1.2. Individual abundance distributions derived from color-magnitude diagrams at each pointing. Each histogram is labeled by our internal identification code and the semimajor axis (in arcsecond) of the corresponding elliptical isophote.

(outer disk) and of globular clusters with blue horizontal branches. Young subpopulations can and probably do exist, injecting a few blue giants into the various fields, but these will not be able to skew the overall abundance distribution very much, though they may add extra width to the distribution.

The procedure is to take the brighter giants, for which the errors are the smallest, and to compare their colors with those of theoretical isochrones. Our method was simply to bin stars that lay between isochrones of various [Fe/H].

1.3 Results

The resulting abundance distributions are shown in Figure 2. The inner three fields, though shown, are nevertheless too crowded to be reliable and are not used in any of the following discussion. They are all within 3 kpc of M31 center. Fields "IN 07" and "IN 04" in our internal numbering scheme have a color transformation problem that we have not yet fully corrected, and thus appear a bit more metal-rich than they should. Looking at the other histograms, two scientific points present themselves.

(1) The halo (perhaps "outer disk" would be a more appropriate term) at about 30 to 50 kpc from the nucleus is metal-rich compared to that of the Milky Way, with [Fe/H] $\approx$ –0.5 rather than ≈ -1.5. Roundly, M31's halo is a factor of ten more metal-rich than the Milky

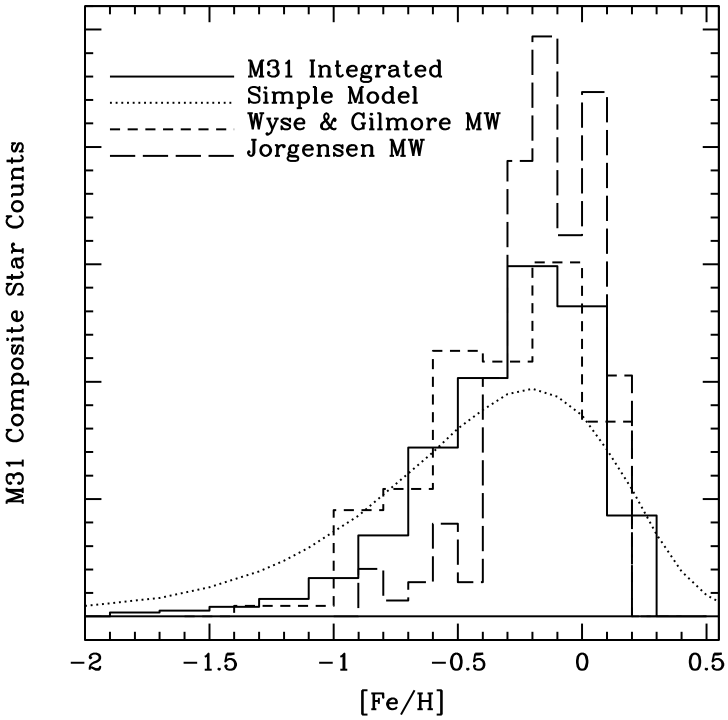

Fig. 1.3. The fully integrated abundance distribution for M31 is shown. For comparison, the analytic Simple model is also shown as a dotted line, along with two derivations of the local solar cylinder abundance distribution; Wyse & Gilmore (1985) and Jørgensen (2000).

Way's. It also seems to be more metal-rich than its own globular cluster system, which has a mean abundance ≤ -1 in a similar spatial region (Reed, Harris, & Harris 1994)

(2) There is a mild abundance gradient, amounting to around 0.4 dex across the span of the data, from about 3 kpc out to 50 kpc.

These individual abundance distributions were weighted and combined to simulate the whole-galaxy abundance distribution: each histogram was weighted by an estimate of the mass near it elliptical annulus and summed to give the combined histogram shown in Figure 3.

The M31 observed closed-box abundance distribution in Figure 3 is compared to the Simple model and two observational distributions for the local solar cylinder in the Milky Way. Errors in the M31 distribution include random observational errors, some systematic error with mapping colors correctly, contamination by young subpopulations, and dust lanes. Correction or deconvolution of these effects will all tend to narrow the distribution. The "raw" M31 abundance distribution rather closely resembles the Wyse & Gilmore (1985) distribution, but we think the true distribution is somewhat more narrow than this, though perhaps not quite as narrow as the Jørgensen (2000) distribution.

If the Milky Way were treated the same way as we treat M31, and all components of disk, halo, and bulge were added up, the abundance distribution would almost certainly be wider than the local one since one would be adding stars with extreme abundances from the halo, outer disk, and bulge. Therefore, it is hard to escape the conclusion that M31 as a whole is more monometallic than the Milky Way.

One of the long-standing problems of chemical evolution modeling is that the models are usually sufficiently flexible to fit almost any set of constraints. Happily, the consideration of the entirety of M31 also removes one very popular degree of freedom; that of inflow and outflow. From astrophysical plausibility one can argue that almost all of the intergalactic gas that accreted onto M31 is still there, so outflow is negligible. Inflow has nowhere to flow *to*, so inflowing gas must be turned into stars (except the 2% that has not). In short, M31 must be a fairly good closed box. If we can no longer turn to inflow/outflow models to explain the narrowness of its abundance distribution, it is highly probable that some kind of prompt initial enrichment mechanism must have operated during at least one formation episode in the proto-M31 environment. Whether this involved a variable initial mass function, especially violent merging episodes, or other mechanisms remains to be seen. Future work, especially on abundance ratios, may reveal more detail.

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