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THE CHEMICAL COMPOSITION OF POPULATION I STARS

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ABSTRACT

A comparison of observed and theoretical mass-luminosity relations for unevolved stars in high-mass eclipsing binary systems and in low-mass visual binary systems is used to find the hydrogen and metals abundances of Population I stars: $X = 0.69 \pm 0.12$ and $Z = 0.036 \pm 0.039$. Alternatively, by adopting $Z = 0.03 \pm 0.01$, one finds $X = 0.71 \pm 0.03$. Limitations of the method are discussed briefly.
Subject headings: abundances, stellar — interiors, stellar — mass-luminosity relation

The most reliable methods of determining the chemical composition of Population I stars involve (1) a comparison of observed spectral features of stars (and of emission nebulae) with theoretical model atmospheres and (2) a comparison of measured masses and luminosities of stars in binary systems with theoretical model interiors. Present spectroscopic evidence suggests that $N(\mathrm{He})/N(\mathrm{H}) = 0.10 \pm 0.02$ (e.g., Norris 1971) and $Z = 0.03 \pm 0.01$ (e.g., Morton 1968), implying that $X = 0.69 \pm 0.04$, where X and Z are the hydrogen and metals abundances by mass, respectively. But systematic errors in X and Z could be twice the quoted errors. The purpose of the present paper is to try to reduce the uncertainty in X and Z by using method (2) and, simultaneously, to check current theoretical model interiors by comparing the results of methods (1) and (2).

A new investigation of massive (5–60 $\mathfrak{M}_\odot$) members of eclipsing binary systems having reliable masses (Batten 1968) and reliable luminosities (Stothers 1973) has yielded six stars that are essentially unevolved, i.e., that have radii close to the empirical zero-age main-sequence (ZAMS) radii implied by the calibrations of Blaauw (1963) and of Morton and Adams (1968). These six stars are the components of Y Cyg, V453 Cyg, and AH Cep; their masses range from 14 to 18 $\mathfrak{M}_\odot$, and they define a tight mass-luminosity relation, for which $M_{\mathrm{bol}} = -6.0 \pm 0.2$ at 15 $\mathfrak{M}_\odot$ (the observational error of M_{bol} for a single star is estimated to be ± 0.5 mag).

Theoretical models of unevolved (ZAMS) stars of 15 $\mathfrak{M}_\odot$ that are nonrotating and nonmagnetic have been constructed for a variety of chemical compositions by Stothers (1972*a*), using CS opacities (Cox and Stewart 1965). Systematically larger opacities have been obtained by CMS (Carson, Mayers, and Stibbs 1968), whose few available opacity points can be represented approximately by multiplying the absorption part of the CS opacities by a factor $\max\{1, (3 - |6 - \log T|)\}$. A second set of ZAMS models has been calculated with the modified CS opacities, for the same chemical compositions used previously. The new models for 15 $\mathfrak{M}_\odot$ are slightly cooler than before, by about 0.04 in $\log T_e$, and slightly fainter, viz.,

$$M_{\mathrm{bol}} = -6.0 + 3.8(X - 0.70) + 6.7(Z - 0.03) \qquad [\mathrm{CS}]\,;$$

$$M_{\mathrm{bol}} = -5.9 + 4.0(X - 0.70) + 10.7(Z - 0.03) \qquad [\mathrm{CMS}]\,.$$

Introducing the empirical value $M_{\mathrm{bol}} = -6.0 \pm 0.2$ into the theoretical relation based on CS opacities, we obtain

$$X = 0.70(\pm 0.05) - 2(Z - 0.03)\,.$$

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If CMS opacities are adopted, X is smaller by 0.02. If the older KM opacities (Keller and Meyerott 1955) are used (cf. the 15 $\mathfrak{M}_\odot$ model of Iben 1966), then X is smaller by less than 0.01. Carson (private communication) suggests that possibly the CS and CMS opacities bracket the "true" opacities. Since the CMS opacities were originally calculated for higher densities than those attained in our models and were based on the Thomas-Fermi approximation, whose deviations from the hydrogenic approximation used by CS are expected to be more important at higher densities, our simple modification of the CS opacities is probably exaggerated at 15 $\mathfrak{M}_\odot$. Furthermore, Nikiforov and Uvarov (1970) also used the Thomas-Fermi approximation for their opacities and found better agreement with CS. We shall therefore adopt the models based on CS opacities for the present time. The relative insensitivity of the derived value of X to the metals abundance (and to atomic absorption generally) is due to the predominance of electron scattering in the opacity of high-mass stars. The even greater insensitivity of X to errors in the nuclear reaction rates is also simple to demonstrate (cf. the 16 $\mathfrak{M}_\odot$ models of Ziołkowski 1967).

For low stellar masses our value of X derived from stars of high mass can be adopted to find Z by the same method. We shall here employ the main-sequence (dwarf) members of visual binary systems having reliable (usually trigonometric) parallaxes. The empirical masses range from 0.07 to 5 $\mathfrak{M}_\odot$, but only those below $\sim$2 $\mathfrak{M}_\odot$ are reliable or numerous, while masses below $\sim$0.6 $\mathfrak{M}_\odot$ will be excluded here because the theoretical models for stars of very low mass are rather uncertain. In the adopted mass range the bolometric corrections are small, but, for the sake of consistency with other work to be discussed, we have adopted Harris's (1963) values. Cester (1965) gives for 183 dwarf (including some subgiant) members of visual binary systems:

$$M_{\rm bol} = 4.95(\pm 0.03) - 10.95(\pm 0.18) \log \mathfrak{M}/\mathfrak{M}_\odot ,$$

while the highly reliable data of van de Kamp (1971) for seven dwarf members nearest the Sun (and including the Sun) yield

$$M_{\rm bol} = 4.9(\pm 0.1) - 10.6(\pm 0.7) \log \mathfrak{M}/\mathfrak{M}_\odot .$$

The excellent agreement between these two relations is confirmed if we use the extensive, but still mostly reliable, data for 48 dwarf members from Harris, Strand, and Worley (1963), which yield $M_{\rm bol} = 4.95 \pm 0.15$ at 1 $\mathfrak{M}_\odot$. Recently McCluskey and Kondo (1972) have considered $\sim$300 dwarfs with masses of 0.3 to 30 $\mathfrak{M}_\odot$ (about 20 percent in eclipsing binary systems), and have found $M_{\rm bol} = 4.89 \pm 0.14$ at 1 $\mathfrak{M}_\odot$. The brighter mass-luminosity relations found by Ruben and Masevich (1966) and by Morton and Adams (1968) were based on a smaller selection of stars from Harris *et al.* (1963) than we have used; and the anomalous mass-luminosity relation derived by Eggen (1965, 1967) for the Hyades cluster and Pleiades group has not been confirmed by Alexander (1968, 1972), who also finds no significant differences between the 1–2 $\mathfrak{M}_\odot$ members of the Hyades group, the Sirius group and UMa cluster, and the nearby field.

Theoretical models for ZAMS stars of 0.7–2 $\mathfrak{M}_\odot$ have been computed by Copeland, Jensen, and Jorgensen (1970), by Ezer and Cameron (1965, 1967), and by Sackmann (1970), all incorporating CS opacities, and these models are in fairly good agreement among themselves and with similar models calculated over part of this mass range by Kelsall and Strömgren (1966) and by Reiz, Petersen, and Hejlesen (1968). At 1 $\mathfrak{M}_\odot$, the models predict

$$M_{\rm bol} = 4.9(\pm 0.2) + 6.9(X - 0.70) + 23.0(Z - 0.03) ,$$

while, at 2 $\mathfrak{M}_\odot$, they predict

$$M_{\rm bol} = 1.60(\pm 0.05) + 5.3(X - 0.70) + 17.0(Z - 0.03) ,$$

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where the error estimates reflect small differences among the models computed by different authors (due to different nuclear reaction rates, different versions of the CS opacities, etc.).

Introducing the empirical values $M_{\text{bol}} = 4.95 \pm 0.10$ at $1\,\mathfrak{M}_\odot$ and $M_{\text{bol}} = 1.65 \pm 0.10$ at $2\,\mathfrak{M}_\odot$, we find, respectively:

$$X = 0.71(\pm 0.03) - 3(Z - 0.03)\,, \qquad X = 0.71(\pm 0.02) - 3(Z - 0.03)\,.$$

At $1\,\mathfrak{M}_\odot$, use of the CMS or KM opacities would reduce X by ~ 0.14 or ~ 0.04, respectively (cf. the $1\,\mathfrak{M}_\odot$ models of Stothers and Ezer 1973; Iben 1967). At $2\,\mathfrak{M}_\odot$, their use would make respective reductions of ~ 0.07 and ~ 0.01 (cf. the $2.25\,\mathfrak{M}_\odot$ models of Novotny 1972; Iben and Ehrman 1962). However, we adopt the CS opacities for reasons given above.

By combining our derived X-Z relation for 1 or $2\,\mathfrak{M}_\odot$ with that for $15\,\mathfrak{M}_\odot$, we can solve for X and Z separately, obtaining $X = 0.69 \pm 0.12$ and $Z = 0.036 \pm 0.039$. These values are in good agreement with the spectroscopically observed values. They are also close to values recently derived for a number of eclipsing binary systems containing stars of mostly low and intermediate masses (Percy and Demarque 1967; Strömgren 1967; Ziołkowski 1967; Morton 1968; Copeland *et al.* 1970; Popper *et al.* 1970; Stothers 1972*a*). Although these previous investigations were unable to determine X and Z separately from the mass-luminosity relation, our present determination of Z cannot be considered secure until the opacity problem is cleared up. The same difficulty afflicts the determination of Z by using the mass-radius relation. Therefore, it is better to adopt $Z = 0.03 \pm 0.01$, whereupon our data yield $X = 0.71 \pm 0.03$.

Our approach shares the common drawback of the binary-system method in that it must assume a unique set of X and Z for all masses concerned. Although stars of 2 and $15\,\mathfrak{M}_\odot$ are probably chemically similar (on the average) because of their relatively young ages, this need not be true for a mixture of "young" and "old" stars of $1\,\mathfrak{M}_\odot$ if the interstellar medium has appreciably evolved in time. The most reliable information on this question comes from abundance determinations for the Sun based on spectroscopic, cosmic-ray, and meteoritic data; these currently yield $X = 0.79$ and $Z = 0.016$ (Ezer and Cameron 1971)—values which are at least consistent with our derived X-Z relation for $1\,\mathfrak{M}_\odot$ stars. But to complicate matters further, a number of other old stars seem to exhibit a "supermetallicity" with respect to the Sun (Spinrad and Taylor 1969; Nissen 1970), although, unfortunately, their helium abundances have not yet been well determined. Despite these uncertainties, cosmic variations in X and Z due to different times and places of stellar origin, as well as possible secular fluctuations of stellar luminosity, would tend to average out in a large sample of stars.

The second drawback of the binary-system method is that, if the stars are systematically evolved (brighter than ZAMS stars), then X should be increased. Our sample of high-mass stars is essentially unevolved, and the same is probably true enough for our purposes for the average of the low-mass stars. Of course, this statement does not refer to the very uncertain determination of Z.

A third possible drawback is the neglect of magnetic fields in the theoretical models. However, magnetic fields have already been shown to be almost certainly too weak to significantly affect the luminosity of stars of high mass (Stothers 1972*b*; Stothers and Chin 1973) as well as those of low mass (Bahcall and Ulrich 1971; Chitre, Ezer, and Stothers 1973).

A fourth possible drawback is the neglect of axial rotation. However, uniform rotation, even at breakup velocity, changes the stellar luminosity very little. But, if the stars are in fast nonuniform rotation with angular velocity increasing markedly toward the center (Mark 1968; Bodenheimer and Ostriker 1970; Bodenheimer 1971), the predicted luminosities of the stars and hence the derived X should be decreased.

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In the case of our sample of unevolved stars of high mass in eclipsing (close) binary systems, tidal forces are expected to have largely synchronized their axial rotations and orbital revolutions, as is approximately observed (Stothers 1973). Tidal forces, however, are not at work among the members of visual (wide) binary systems, which have probably evolved as essentially independent stars (Slettebak 1963; van Albada 1968). But the slowness of their observed rotational velocities, which are normal for their spectral types (Slettebak 1963), and the normality of the observed relation between their masses and spectral types (Stephenson and Sanwal 1969), argue against fast nonuniform rotation. Furthermore, among single stars of known luminosity (based preferably on a geometrical parallax), atmospheric analysis of the spectrum can yield directly the mass (e.g., Bless 1960). Within large probable errors, the "atmospheric" mass-luminosity relations observed for Hyades cluster members ($\sim 2\mathfrak{M}_\odot$—Conti, Wallerstein, and Wing 1965; Oke and Conti 1966) and for Sco OB2 members ($\sim 15\mathfrak{M}_\odot$—Watson 1972) are normal; an upper limit on the amount of possible underluminosity can be set at 1 mag. It is worth mentioning that, in principle, X and Z could be derived by this method if the surface gravities were determined more accurately.

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