Neon and Chemical Fractionation Trends in Late-type Stellar Atmospheres

David García-Alvarez*,†, Jeremy J. Drake** and Paola Testa***‡

*Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
†GTC CALP, E-38712 San Antonio, La Palma, Spain, david.garcia@gtc.iac.es
**Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

Abstract. A survey of Ne, O and Fe coronal abundances culled from the recent literature for about 60 late-type stars confirms that the Ne/O ratio of stellar outer atmospheres is about two times the value recently recommended by Asplund et al. The mean Ne/O remains flat from the most active stars down to at least intermediate activity levels (−5 < L_X/L_bol < −2), with some evidence for a decline toward the lowest activity levels sampled. The abundances surveyed are all based on emission measure distribution analyses and the mean Ne/O is about 0.1 dex lower than that found from line ratios in the seminal study of mostly active stars by Drake & Testa (2005), but is within the systematic uncertainties of that study. We also confirm a pattern of strongly decreasing Fe/O with increasing stellar activity. The observed abundance patterns are reminiscent of the recent finding of a dependence of the solar Ne/O and Fe/O ratios on active region plasma temperature and indicate a universal fractionation process is at work. The firm saturation in stellar Ne/O at higher activity levels combined with variability in the solar coronal Ne/O leads us to suggest that Ne is generally depleted in the solar outer atmosphere and photospheric values are reflected in active stellar coronae. The solution to the recent solar model problem would then appear to lie in a combination of the Asplund et al. (2005) O abundance downward revision being too large, and the Ne abundance being underestimated for the Sun by about a factor of 2.

Keywords: stars: abundances - stars: activity - stars: coronae - X-rays: stars

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INTRODUCTION

The interior structure of the Sun can be studied with great accuracy using observations of its oscillations, similar to seismology of the Earth. Precise agreement between helioseismological measurements and predictions of theoretical solar models has been a triumph of modern astrophysics [4]. However, a recent downward revision by 25-35% of the solar abundances of light elements such as C, N, O and Ne [3] has broken this accordance: models adopting the new abundances incorrectly predict the depth of the convection zone, the depth profiles of sound speed and density, and the helium abundance [4]. The discrepancies are far beyond the uncertainties in either the data or the model predictions [5].

Drake & Testa [7] reported on neon abundances relative to oxygen measured in a sample of nearby solar-like stars from their X-ray spectra. The results were very similar for all stars and substantially larger than the recommended solar value of Ne/O=0.15 by number [1, 3]. If the Ne/O abundance in these stars is adopted for the Sun the models are brought back into agreement with helioseismology [2]. However, the stellar sample
FIGURE 1. The coronal Ne/O abundance ratio for the stellar sample expressed relative to the solar photospheric value of Asplund et al. [3] \((n(\text{Ne})/n(\text{O})=0.15\) by number). The highest value found is for the T Tauri star TW Hya and was been interpreted by Drake et al. [8] in terms of gain depletion of metals in gas emitting X-rays from an accretion shock. The mean \([\text{Ne}/\text{O}]\) illustrated was computed omitting this point.

OBSERVATIONS AND DATA ANALYSIS

Our sample is based on analyses of high resolution \textit{Chandra} and \textit{XMM-Newton} spectra culled from the recent literature for about 60 late-type stars, including dwarfs, giants, tidally-interacting binaries and pre-main sequence stars. It covers a wide range of activity regimes \((-2 < \log L_X/L_{\text{bol}} < -7\) and spectral types (mid-F to mid-M). We examined the coronal Fe/O and Ne/O ratios for these stars using the abundances derived from differential emission measure distribution analyses performed in the various literature used by Drake & Testa [7] for their abundance analysis contains mostly active stars and binary systems, which are not comparable to the Sun in terms of activity and tend to exhibit different outer atmosphere chemical fractionation patterns. Hence it is also necessary to determine the Ne/O ratio in relatively inactive stars that are comparable to the Sun. In this work we analyse a sample three times larger than that of Drake & Testa [7], including about 20 low activity stars \((\log L_X/L_{\text{bol}} < -5)\).
FIGURE 2. The coronal Fe/O abundance ratio expressed relative to the Asplund et al. [3] solar photospheric mixture in the usual spectroscopic logarithmic bracket notation for the stellar sample. The Herbig Ae pre-main sequence star AB Aurigae is the only deviant point from the well-defined trend of decreasing Fe/O ratio with increasing stellar activity.

studies. In the following, the coronal Fe/O and Ne/O abundance ratios are expressed relative to the Asplund et al. [3] solar photospheric mixture for the stellar sample.

DISCUSSION AND CONCLUSION

The mean Ne/O of our stellar sample is about twice the value recently recommended for the solar photosphere [3] and the average of estimates for the solar corona, and about 0.1 dex lower than the mean estimated by Drake & Testa [7] from line ratios for a sample of mostly active stars, but is within the systematic uncertainties of the latter study (see Fig.1).

There is no significant dependence of coronal Ne/O on the stellar activity indicators $L_X/L_{bol}$ or Rossby number, though the lowest activity stars of the sample present some evidence of a decline in Ne/O for $L_X/L_{bol} < 6$ and solar-like activity, as has also been suggested in a recent study of the same stars [10]. For higher activities Ne/O, for dwarfs is statistically consistent with a constant value $[\text{Ne/O}]=0.3$ with observational scatter of
about 0.1 dex.

In contrast to Ne/O, the Fe/O ratios vary by more than order of magnitude with a clear trend of decreasing Fe/O with increasing activity (see Fig.2). Low to intermediate activity stars with \( L_X / L_{bol} < -4.5 \) tend to have enhanced Fe/O compared with photospheric expectations (quasi-solar for most of the stars in the sample) indicative of a solar-like FIP effect. At higher activity levels, Fe/O exhibits a strong decline with increasing activity in all the types of stars sampled, including pre-main sequence stars.

The observed abundance patterns are reminiscent of evidence for a dependence of the solar Ne/O and Fe/O ratios on active region plasma temperature \([6]\) and indicate a universal fractionation process is at work. The apparently constant stellar Ne/O over a wide range in activity level combined with variability observed in the solar coronal Ne/O leads us to suggest that Ne is generally depleted in the solar outer atmosphere, whereas photospheric values are reflected in more active stellar coronae.

If this is the case, the solution to the recent "solar model problem" - solar models using the Asplund et al. \([3]\) composition containing too little metal opacity to match helioseismic observations - is a combination of the Asplund et al. \([3]\) O abundance downward revision being too large, and the Ne abundance being underestimated for the Sun by about a factor of 2.

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