A New Isotopic Abundance Anomaly in Chemically Peculiar Stars

The discovery of a new isotopic anomaly in young, chemically-peculiar stars draws attention to extraordinary chemical separation processes that must take place in the atmospheres of these stars. No other natural processes are known that can do this so efficiently.

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Stellar astronomers recently found a rare calcium isotope. They discovered ^{48}Ca on ESO spectra taken with the UVES echelle spectrograph. The dominant isotope of calcium is usually ^{40}Ca, with 20 protons and 20 neutrons. The relatively large neutron excess in ^{48}Ca (28 neutrons) makes it difficult to explain this isotope within the standard schemes of the origin of the elements. Almost any process that would make ^{48}Ca would overproduce other neutron-rich isotopes.

Isotopic anomalies have been found for other elements, notably in helium, mercury, and platinum. It appears there is a class of star capable of separating isotopes with astonishing efficiency!

The Chemically Peculiar Stars

The stars with isotopic anomalies are members of a diverse group with unusual and sometimes bizarre surface compositions. They are now called CP stars, where the "CP" stands for chemically peculiar. This notation was introduced to describe chemically peculiar *main-sequence* stars – stars still converting hydrogen to helium in their interiors. These CP stars lie on the *upper*, hotter part of the main sequence. Their spectral types range roughly from early B to middle F. The group defined here does not include objects where the surface compositions have been altered by internal nuclear reactions.

Quantitative analyses of CP stars show that the abundances of certain elements can vary by many orders of magnitude from those in the sun. An element can be overabundant by as much as a factor of a million (10^6). Most abundance anomalies in CP stars are not so extreme, ranging typically from being marginally detectable to perhaps a factor of a thousand.

Isotopic Anomalies

Isotopic anomalies in the elements helium and mercury were discovered in the 1960's. For some time, these were the only cases of isotopic anomalies known in CP stars. Other isotopic abundance anomalies are now known, in platinum and thallium – both quite heavy elements. It is interesting that in all these cases, the heavy isotopes are increased in abundance.

The Discovery of ^{48}Ca in Stellar Spectra

In the summer of 2004, Fiorella Castelli and Swetlana Hubrig announced the discovery of ^{48}Ca. This was the first indication of an isotopic abundance variation of a light element since the discovery in the 1960's of the ^{3}He stars. They studied lines of singly ionized calcium (Ca II) belonging to the *infrared triplet*. Figure 1 shows the relevant energy levels, and the strongest lines of Ca II. Wavelengths in the infrared triplet have significant shifts, for ^{48}Ca vs. the common isotope, ^{40}Ca. These shifts owe their existence to the subtle interactions of the 3d electrons with the atomic nuclei.

Stellar Observations of ^{48}Ca

Figure 2 shows regions of a stellar spectrum studied in great detail by Castelli and Hubrig (2004). The upper part of the figure shows typical fits of the observed (black) and computed (red) spectra. The wavelength shifts here are of the order of 0.001 nm. Contrast the fits in the upper part of Figure 2 with those in lower two panels, showing the Ca II lines. The calculated features are some 0.02 nm to the violet of the observed lines. Shifts of this magnitude cannot possibly be due to a measurement error. Using laboratory measurements by Nörterhäuser et al. (1998), Castelli and Hubrig found that excellent fits to the stellar profiles can be obtained if calcium is assumed to be 97 % ^{48}Ca.

Cowley and Hubrig have been working on UVES spectra of a different variety of CP stars. Wavelengths of the infrared triplet were available for several of them. Interestingly, the Ca II lines in the most peculiar of their stars, the notorious Przybylski's star, appeared to show the ^{48}Ca shifts. When another spectrum of the same star, obtained with a different spectrograph also indicated ^{48}Ca, they decided to measure additional spectra, concentrating on magnetic CP stars, but including a few other exotic types. Eventually, they assembled the 22 wavelength measurements for CP stars displayed in Figure 3.

Figure 3 shows that the two wavelengths are correlated – both are shifted by roughly the same amount. This is just what would be expected if the stars had differing admixtures of ^{48}Ca, with points for nearly pure ^{48}Ca at the upper right. The cluster of points at the lower-left corner indicates a normal (solar) isotopic mix. If the discordant measurements were caused by blending or instrumental effects, such a correlation is much less likely.

The third line of the Ca II triplet has been unavailable for most stars, because of the settings of the UVES spectrograph. Fortunately, beginning in April 2005, new settings make it possible to observe all three lines simultaneously.

What Does It Mean?

Since the pioneering work of Georges Michaud in 1970, abundance anomalies in CP stars have come to be recognized as due primarily to chemical separation. Atoms in the atmospheres of stars are subject to gravitational settling and an opposing outward force due to radiation. The theory of chemical separation has been highly successful in explaining the overall chemical anomalies of the CP stars.

Isotopic anomalies are difficult to explain. A most notorious anomaly occurs for stars where the heaviest stable isotope of mercury, ^{204}Hg, is the most abundant. Here, a scheme is required to push out the lighter isotopes from the star's photosphere, while preventing replenishment from below.

The ^{48}Ca anomaly is the first of its kind to be established in the magnetic sequence of CP stars. It is significant that we find the ^{48}Ca anomaly over a wide range of effective temperatures and atmospheric conditions.

While details of the isotopic fraction processes discussed here are uncertain, one fact is clear. These CP stars have by far the most unusual natural fractionation mechanism known.

References

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Cowley, C. R. & Hubrig, S. 2005, A&A 432, L21
Nörterhäuser, W., Blaum, K., Icker, P., et al. 1998, Eur. Phys. J. D2, 33

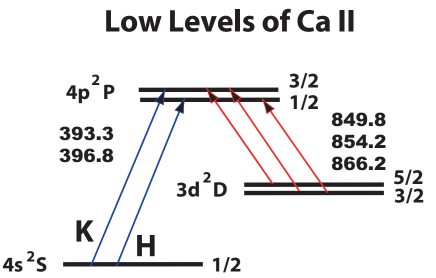

Figure 1: Partial energy-level diagram for the one-electron spectrum Ca II. Fraunhofer's H and K lines connect the ground 4s^{2}S-term to the first term to which an allowed transition is possible. These lines are known as resonance lines. Transitions from the ground term to the 3d^{2}D-term are forbidden, but transitions from the 3d^{2}D- to the 4p^{2}P-term are allowed, and form the infrared triplet.

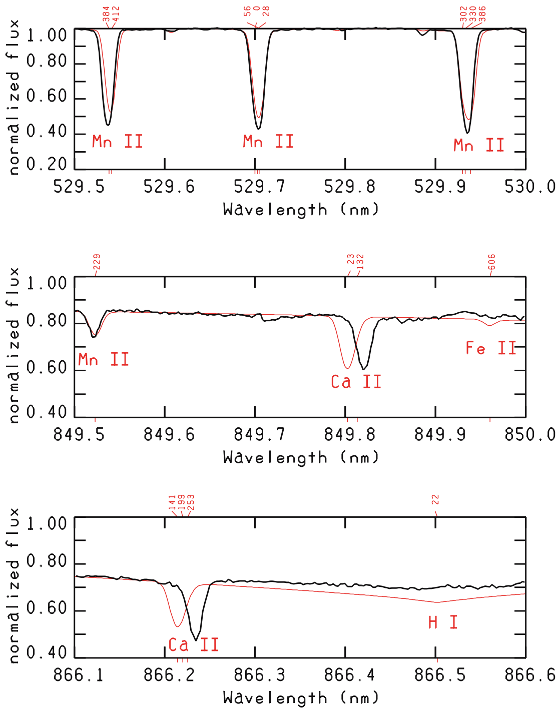

Figure 2: Discovery observations of ^{48}Ca. Most spectral features in HR 7143 (HD 175640, shown in black) could be well matched by calculations shown in red. The upper panel is typical. The central and bottom panels show the region of two lines of the infrared triplet, where it is seen that the stellar feature is shifted to longer wavelengths by 0.2 Å (0.02 nm). These shifts are just what would be expected if the calcium were mostly present as the isotope ^{48}Ca.

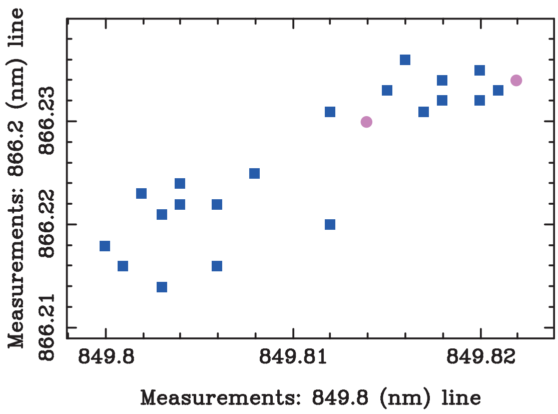

Figure 3: Stellar wavelengths for Ca II 866.2 nm vs. 849.8 nm. The points are wavelength measurements for two lines of the infrared triplet. The laboratory wavelengths are 849.802 nm and 866.214 nm. Two points in purple are from the original discovery by Castelli and Hubrig, made for non-magnetic CP stars. The blue points are measurements for the same transitions but in magnetic CP stars.

The photo zooms-in on the LMC H II region N214C. The field size is 193″ × 201″ corresponding to roughly 160 × 170 light-years. The brightest object, situated toward the middle of the nebula, is the Sk-71 51 cluster. A striking compact H II blob lies ~ 60″ (~ 50 light-years) north of Sk-71 51. *ESO PR Photo 12b/05.*