The Abundance of Iron in the Sun and the Meteorites

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Abstract

It has long been a puzzle that the solar corona appears to be overabundant in metals relative to the photosphere, and that relative to its neighbors iron is a factor four underabundant in the photosphere relative to meteorites. It is suggested that metals are concentrated in the corona by radiation pressure acting on lines, and that the solar wind has carried away much of the iron in the outer solar convection zone.

A long-standing problem which plagues attempts to construct theories of nucleosynthesis and of the origin of the solar system is the discrepancy between the solar and meteoritic abundances of iron. Relative to other intermediate elements, iron is about a factor four less abundant in the solar photosphere than in the meteorites. The observational and experimental background of this problem has many times been discussed by Urey (see for example Urey 1967).

One of the features contributing to this puzzle is the lack of agreement in determinations of the abundances of the metals in the photosphere and corona. The metals generally appear to be overabundant in the corona relative to the photosphere. Perhaps the worst offender in this regard is iron, which Pottasch (1963) has found to be overabundant by a factor 20 in the corona relative to the photosphere.

The concentration of metals in the corona can probably be understood as a result of radiation pressure acting on their lines. The absorption cross section at the center of a line having an oscillator strength of unity is $\sim \lambda^2$, where λ is the photon wavelength. However, the line half-width is only $\sim 10^{-7}$ of the width of the Planck spectrum. In a metal with many lines, the oscillator strength will be divided among them, thereby allowing the atom to absorb a significant fraction of the energy of impinging radiation.

The force acting on a gram of some element due to radiation pressure is

$$F_{rad} = \frac{kqL}{4\pi cR^2} \qquad (1)$$

where L is the solar luminosity, R the solar radius, k the mean absorption coefficient in cm^2/gm in the fraction q of the spectrum, and c is the velocity of light. The gravitational force acting on the same gram is

$$F_{grav} = \frac{GM}{R^2} \quad , \tag{2}$$

where G is the gravitational constant and M is the mass of the sun. For an intermediate element, the force due to radiation pressure on one or more lines with total oscillator strength unity exceeds the gravitational force by two orders of magnitude.

The Los Alamos Opacity Code allows inclusion of about a dozen elements in the mixture for which an opacity is to be calculated, of which about eight are usually intermediate metals. For solar photospheric conditions, the lines increase the calculated Rosseland mean opacity by a factor 1.3. This means that about one-quarter of the spectrum is obscured by heavily-absorbing lines, far more than necessary by the above criterion.

This consideration would apply only if the full Planck spectrum were incident on the atoms. In fact, the lines tend to be formed at optical depths $\sim 10^{-2}$, where the optical depth is measured with respect to the continuum, so that the majority of the effective part of the Planck spectrum is greatly reduced by self-shielding. For an element like iron, the radiation pressure exerted collectively on all the atoms in the outer 10^{-2} or 10^{-1} of the optical depth is not sufficient to overcome gravitational forces.

However, in the outer solar atmosphere the decreasing density and increasing temperature (toward the chromosphere) will produce new stages of ionization. The number of ions in these stages will be too few for self-shielding to be important, and hence radiation pressure can exceed gravity. Diffusion outwards is then assisted by the low density but impeded by transverse magnetic fields. When the ion reaches the corona and becomes still more fully ionized, the number of lines in the visible part of the spectrum will diminish and radiation pressure will no longer be dominant.

If we accept the reality of the overabundances of metals in the corona, then we should consider how rapidly these will be removed from the sun by the solar wind. Since some gravitational settling of these ions occurs in the corona (Parker 1963), such loss of ions should vary with the strength of the solar wind. But since radiation pressure should prevent the ions from returning to the photosphere, the loss in the solar wind should on the average be the same as the outward diffusion rate from the upper atmosphere of the sun.

Typical values measured for the solar wind at the earth for the density and velocity are 10 ions/cm.^{3} and $5x10^7$ cm/sec. This corresponds to a loss of mass by the sun of $2.8x10^{12}$ gm./sec., if it is assumed that the solar wind is isotropic. In $4.5x10^9$ years the accumulated mass loss at this rate would be $4x10^{29}$ grams.

It should be expected that the solar photosphere will readily exchange mass with the outer convection zone of the sun. In a published study of solar evolution, it was found that the outer convection zone now contains 0.012 of the solar mass (Ezer and Cameron 1965). More recent improved models obtained by Mrs. Ezer have only 0.008 of the solar mass in the outer convection zone. Thus it appears that about 0.025 of this convection zone has been depleted by the solar wind during the lifetime of the sun. Hence, if iron is overabundant in the corona by a factor 20, then 0.5 of the iron in the outer convection zone would be lost.

This is not greatly different from the 0.75 or 0.8 loss of iron which would be required to account for the abundance discrepancy between the photosphere and the meteorites. The additional loss of iron might readily occur if the solar wind is stronger at middle solar latitudes than near the equator, owing to the greater solar activity and consequent greater coronal heating at those latitudes. It must also be required that no significant mixing of matter between the outer solar convection zone and the inner radiative core can have occurred during most of the more recent lifetime of the sun.

Hence I believe that a stronger case can be made for taking a typical meteoritic iron abundance rather than the photospheric abundance as typical of the primitive solar system.

Similar effects may also occur in other classes of stars, but simple predictions are not possible owing to lack of knowledge of coronal compositions and stellar wind mass loss rates. However, if any significant component of the cosmic rays is accelerated in stellar coronas, then detailed abundance anomalies could occur due to selective enrichment of certain elements in those coronas.

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