HALONS: MASSIVE DARK-MATTER CANDIDATES

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Abstract. Halons are the hypothetical massive elementary components of the galactic halo. They accrete steadily on to stars; a significant internal stellar energy sink results from their presence in a low-mass star. It is shown that halons could solve the solar neutrino problem and the problem of the galactic age.

1. Halons

Halons (Finzi, 1986, 1987) are the hypothetical massive elementary components of the non-baryonic galactic halo: they accrete steadily on to stars; their presence in a low-mass star causes a significant internal energy sink and speeds up evolution.

We make the following assumptions with regard to halons:

(i) They are stable particles of mass \( m_h \sim 4m_p \), which do not coincide with their antiparticles.

(ii) For energies \( \lesssim 10^5 \) eV their cross-section for collisions with nucleons is \( \sigma_h \sim 2 \times 10^{-37} \) cm\(^2\). In collisions, a fraction \( \varepsilon \) of the energy available in the frame of reference of the center of mass is emitted on the average in the form of easily escaping 'dark radiation'. \( \varepsilon \) is a dimensionless number which should be \( \sim 10^{-3} \).

(iii) With the exception of gravity, long range forces between halons can be neglected. If the carriers of dark radiation are the massless quanta of a pseudo-scalar field strongly coupled to the field of the halons, assumption (ii) is compatible with assumption (iii), since the long range forces between halons resulting from the coupling behave like \( r^{-4} \) (Nussinov, 1987).

(iv) Inside a sphere of galactocentric radius not much larger than that of the solar orbit halons have densities of \( \sim 0.1 \) cm\(^{-3}\) and velocities somewhat larger than those of Population II stars.

The origin of the halon hypothesis can be traced to a model of planetaries presented in a series of papers, which appeared some years ago (Finzi and Wolf, 1971; Finzi et al., 1974; Finzi and Yahel, 1978). It is shown in these papers that a time-independent supersonic flow of matter from the surface of a cold, electron-degenerate star with a \( \sim 0.4 M_\odot \) H-exhausted core and a \( \sim 0.1 M_\odot \) hydrogen-rich outer shell can produce a nebula and a central star with properties remarkably similar to those observed in planetaries. Partial hydrogen-burning, taking place in the flow of matter a few hundred kilometers above the cold surface of the degenerate star, at temperatures of \( \sim 10^8 \) K, provides the energy needed to overcome the gravitational stellar field. The model is surprisingly self-consistent.

This model of planetaries has motivated a long quest for an evolutionary track leading from an asymptotic-giant-branch star to the electron-degenerate progenitor of a

planetary. While this quest has not yet produced a detailed track, it has lead to the firm conclusion that such a track cannot exist unless an energy sink operates in the stellar interior. Unlike the energy sink resulting from neutrinos, this one should be effective even at low temperatures.

One can show (Finzi, 1986) that, in a star of age $t$ and mass $M$ comparable to $M_\odot$, which moves inside a sphere of galactocentric radius not much larger than that of the Sun, the number of halons must be approximately

$$\frac{(M/M_\odot)}{(t/t_\odot)} N_h e^{-1/2},$$

where $t_\odot = 4.6$ Gyr is the assumed solar age and $N_h \sim 10^{45}$ is a free parameter. In a stellar medium of density $\rho$, a halon emits dark radiation at a rate

$$l_h = 2.14 \times 10^{-25} (m_h/m_p)^{-1/2} \rho \bar{T}^{3/2} \text{erg s}^{-1}; \bar{T}$$

denotes the halon temperature.

2. Stellar Models with Halons

Stellar models with halons (Finzi and Harpaz, 1989a, b) seem to provide sensible descriptions of evolving Main-Sequence stars of mass $M \sim M_\odot$. The characteristic properties of these models are an internal energy sink $L_h$, which increases with time faster than linearly, a central temperature $T_c$ lower and a central density $\rho_c$ higher than those of the standard models of the same mass, age, and composition. In the evolving stars halons form an isothermal cloud of temperature $\bar{T} \approx T_c$. The total rate of nuclear energy generation $Q \approx L + L_h$ is larger than that of the corresponding standard models.

Eventually, a shallow central temperature minimum appears. Later, as $L_h$ approaches $L$, at an age to be denoted by $t_h$, $T_c$ decreases to very low values, $\rho_c$ increases to $\sim 8000$ g cm$^{-3}$ and an electron-degenerate minicore of $\sim 0.02 M_\odot$ is formed on a time-scale of $\sim 10^3$ yr. Nuclear burning temporarily stops near the center, where the hydrogen concentration is still $\sim 0.2$, but continues in the surrounding shells. Continuation of the evolutionary models for $t > t_h$ is difficult and exceedingly time-consuming.

The evolutionary model of a star of mass $M$, that accretes halons, is defined by the values of five parameters, the primordial helium abundance $Y$ and metal abundance $Z$, the ratios $m_h/m_p$ and $\beta/e$ and the free parameter $N_h$. (The constant $\beta$ is defined by the statement that the average transfer of energy from ordinary stellar matter of temperature $T$, to the isothermal cloud of halons of temperature $\bar{T}$, that results from the collision of a halon with a nucleon, is given by $\beta k(T - \bar{T})$.)

In evolutionary solar models with halons $M$ is equal to $M_\odot$, while $Y$ and $Z$ are also approximately known. The choice of $m_h/m_p$, $\beta/e$, and $N_h$ is restricted by the relation $L(t_\odot) = L_\odot$ and the condition that the predicted rate of capture of solar neutrinos by $^{37}$Cl must be consistent with the result of the Davis experiment. Some basic properties of five different solar models are presented in Table I; as shown in that table, the predicted neutrino capture rates by $^{71}$Ga are appreciably larger than those predicted by standard solar models.

The choice of the parameters, that can lead to acceptable solar models, is further