Dark matter and x-ray clouds

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In two previous papers defending the notion of baryonic matter in the universe, the author showed that despite the high temperature of x-ray clouds, $T \sim 10^7$ K, the presence of condensed dark matter is compatible with the baryonic nature of the dark matter by virtue of the clouds' low density. The present paper discusses the origin of baryonic dark matter. © *1994 American Institute of Physics.*

1. INTRODUCTION

In two previous papers,[1,2] the author showed that in contrast to the opinion held by most astrophysicists, dark matter in the universe is most likely baryonic, and is probably described by a mass distribution function consistent with that established for meteors, meteorites, and asteroids:[3] $f(M) \propto M^{-2}$ over the range 10^{-12} g to 10^{20} g. The problems entailed by the idea of baryonic dark matter are probably no worse than those incurred by as yet unobservable particles with $m_\nu c^2 \sim 10$ eV (masses $m_\nu c^2 \sim 10^2$ eV or higher are forbidden[2,4]). These problems, however, can probably be overcome.

In the present paper, I show that the existence of dark matter in x-ray clouds with $T \sim 10^7$ K is compatible with its being baryonic, by virtue of the low density of those clouds.

Cosmic x rays were detected in 1962, as soon as the appropriate instruments were carried by satellites above the atmosphere. Full-time studies began with the 1978 launch of the Einstein Observatory (HEAO-2) into low Earth orbit, and have continued to the present day.[5–9]

Quasistationary x-ray sources (plasma clouds) have been observed in isolation (these may include the Lacertids), but they are normally found in clusters of galaxies, where they tend to surround both the galaxies themselves and the clusters as a whole. The x-ray emission implies plasma temperatures ranging from $\sim 3 \cdot 10^6$ K to $\sim 10^8$ K. The relations among the observable properties of these clouds—their mass M, temperature T, luminosity L, and size R—further imply that they harbor an order of magnitude more unobservable dark matter—missing mass—than luminous material.

In the opening sections of this paper, internal parameters of a spherical plasma cloud such as the electron density n, the ratio of dark matter to observable matter S, the logarithm of the transparency θ, the quasisteady lifetime t, and other properties are expressed in terms of the observables M, T, L, and occasionally R.

We then go on to discuss the nature of the dark matter, with preference given to baryonic matter.[1,2] We show that baryonic dark matter consisting of condensed matter[1] can indeed exist inside plasma clouds with $T \sim 10^7$ K.

We conclude by discussing the origin of baryonic dark matter, which as proposed here constitutes the missing mass.

2. GENERAL CONSIDERATIONS

It would be natural to suppose that the outside of an x-ray cloud is an order of magnitude cooler than its inside. If the radius of a spherical cloud is R_0 and the photon mean free path is l_{ph}, then upon emerging from the central region of the cloud, a photon will undergo an average of $(R_0/l_{\text{ph}})^2$ collisions with electrons. The energy exchanged (usually lost) in each of these collisions is $T^2/m_e c^2$, where m_e is the mass of the electron and c is the speed of light. For a photon not to "cool off," then, we require that $R \ll l_{\text{ph}}(m_e c^2/T)^{1/2}$. Noting that $l_{\text{ph}} = 1/n_e \Phi_0$, where $\Phi_0 = 0.66 \cdot 10^{-24}$ cm^2 is the Thomson cross section, $n \sim M/m_p R_0^3$, and the well known equilibrium relation $R_0 \sim MGm_p/T$ holds (G is the gravitational constant and m_p is the mass of the proton), it can easily be shown that

$$M \gg T^{1.5}(m_e c^2)^{1/2}\Phi_0/G^2 m^3 = 10^{46} \text{ g for}$$

$$T = 0.5 \cdot 10^{-8} \text{ erg} = 0.7 \cdot 10^8 \text{ K}.$$

The masses of x-ray clouds should thus be quite high, just as observed.

It will be desirable in what follows to specify a definite electron density distribution n and dark matter distribution ρ as a function of radius r:

$$n = n_0 \exp(-\pi r^2/R_0^2),$$

$$\rho = \rho_0 \exp(-\pi r^2/r_0^2). \tag{1}$$

These are not fundamental equations; they are merely a matter of convenience.

3. MASS *M*

The distribution (1) yields

$$M = m n_0 R_0^3 + \rho_0 r_0^3, \tag{2}$$

where the first term on the right-hand side is the mass of luminous matter and m is the mass of such matter impinging on a single electron; the second term is the mass of dark matter $m = \mu m_p$, where $\mu = \Sigma n_i A_i / \Sigma n_i Z_i$ for full ionization, with n_i being the concentration of the ith element. The dark matter/ionized gas (plasma) mass ratio is $s = \rho_0 r_0^3 / m n_0 R_0^3$. Ninety percent of the mass of the plasma and dark matter lies at $R \leq R_0$ and $r \leq r_0$, respectively.

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4. TEMPERATURE T

The temperature can be determined via the plasma pressure $P=n'T$, where n' is the total number of particles—electrons plus nuclei—per unit volume of plasma. Here we take $n'=1.9n$. Then

$$T=\frac{P}{n'}=\frac{mG}{1.9}\exp\{\pi R^2/R_0^2\}\int_R^\infty \exp\{-\pi R^2/R_0^2\}dR/R^2$$
$$\times\int_0^R(\exp\{-\pi r^2/r_0^2\}mn_0+\exp\{-\pi r^2/r_0^2\}\rho_0)4\pi r^2dr \tag{3}$$

at $R=0$, i.e., $T(0)=T_0$. The integral in (3) can be evaluated analytically, and

$$T_0=mGR_0^2\cdot 1.05\left[\left(1-\frac{\pi}{4}\right)mn_0+\frac{r_0^2}{R_0^2}\right.$$
$$\left.\times\left(1-\frac{r_0}{R_0}\operatorname{arctg}\frac{R_0}{r_0}\right)\rho_0\right]=1.05\left(1-\frac{\pi}{4}\right)\frac{mGM}{R_0}$$
$$\times\left(\frac{1}{1+S}+\frac{S\operatorname{arctg}R_0/r_0}{(1+S)(1-\pi/4)}\right)=0.226\frac{mGM}{R_0}$$
$$\times\left[\frac{1}{1+S}+\frac{S}{1+S}\frac{(R_0/r_0)-\operatorname{arctg}(R_0/r_0)}{(1-\pi/4)}\right]. \tag{4}$$

The assumption (1) is probably tenable if R_0/r_0 is not too different from 1. But even if R_0/r_0 ranges from 0.8 to 1.25, the second term only ranges from 0.6 to 1.65. For the most part, we assume below that $R_0=r_0$. Then

$$T_0=0.226mGM/R_0\cdots \tag{4a}$$

If, on the other hand, $R\ll R_0$ and $r\ll r_0$, then for $R_0\simeq r_0$,

$$T(R)=\left(T_0-\frac{mG}{1.9}\exp\{\pi R^2/R_0^2\}\right.$$
$$\times\int_0^R\exp\{-\pi R^2/R_0^2\}dR/R^2\int_0^R(mn_0+\rho_0)$$
$$\left.\times 4\pi r^2dr\right)\approx T_0\exp\{-0.553\pi R^2/R_0^2\},$$

or

$$T(R)\approx T_0\left(\frac{n(R)}{n_0}\right)^{0.553}, \tag{5}$$

which corresponds to a polytropic index $0.553^{-1}=1.8$ (the polytropic index for an adiabat is 1.5). In general, the density distribution (1) is largely consistent with the stellar density distribution predicted by polytropic models with indices between 1.5 and 3.5. If $R_0\approx r_0$, the factor 0.226 in (4a) will remain constant as the distribution function (1) is modified within some reasonable limits. Inasmuch as T, M, and R are observable, Eq. (4) provides us with an indication of the departure of the last factor from unity (i.e., information about R_0/r_0 when $S\gg 1$).

5. LUMINOSITY L

The source of x-ray cloud luminosity is almost exclusively electron bremsstrahlung on ions, principally protons. Only at $T<10^6$ K does recombination radiation begin to make inroads,[10] and it becomes the dominant contribution at $T<3\cdot 10^5$ K. The ratio of bremsstrahlung to recombination radiation is proportional to the temperature T.

For bremsstrahlung, the emission rate per unit volume per unit time is[10]

$$W=\frac{2\Phi_0}{137\pi}n\sum_k n_kZ_k^2m_ec^2v_e, \tag{6}$$

where $\Phi_0=(8\pi/3)(e^2/m_ec^2)^2=0.66\cdot 10^{-24}$ cm^2 is the Thomson cross section for light, n_k is the number of nuclei with atomic number Z_k per unit volume, and $v_e=(2T/\pi m_0)^{1/2}$ is half the mean thermal velocity of the electrons. Here we have $\Sigma_kn_kZ_k^2=1.15n$. The total luminosity of the cloud due to bremsstrahlung is

$$L=4\pi\int_0^\infty Wr^2dr=4.3\cdot 10^{-3}\Phi_0n_0^2T_0^{1/2}m_e^{1/2}c^2$$
$$\times\int_0^\infty\exp\left\{-2.28x^2\frac{4x^2dx}{\pi^{1/2}}\right.$$
$$\times R_0^3=1.25\cdot 10^{-3}\Phi_0n_0^2T_0^{1/2}m_0^{1/2}c^2R_0^3. \tag{7}$$

The bremsstrahlung spectral distribution was derived in Ref. 10:

$$\frac{dW}{d\hbar\omega}=\frac{W}{2T}K_0\left(\frac{\hbar\omega}{2T}\right)\exp\left\{-\frac{\hbar\omega}{2T}\right\}, \tag{8}$$

where $K_0(x)$ is the Bessel function of the second kind. To better than 6% accuracy,

$$\frac{dW}{d\hbar\omega}\simeq\frac{W}{2T}\exp\left\{\frac{\hbar\omega}{T}\right\}\ln\left[\left(1+\frac{0.375T}{\hbar\omega}\right)^{1/2}\right.$$
$$\left.+\left(\frac{\pi T}{4\hbar\omega}\right)^{1/2}\right]. \tag{8a}$$

For $\hbar\omega$ at most of order T, $dW/\hbar\omega$ is close to a linear function of T and r over a relatively small temperature range. We can therefore write for the total luminosity over a frequency interval $\Delta\hbar\omega$

$$\Delta L\approx\frac{L}{2T}\exp\left\{-\frac{\hbar\omega}{2T}\right\}K_0\left(\frac{\hbar\omega}{2T}\right)\Delta\hbar\omega, \tag{9}$$

substituting for T the temperature at the maximum of the integrand in (7), i.e., $x=\pi^{1/2}r/R_0=2.28^{-1/2}$, or

$$T=T_0\exp\{-0.553/2.28\}=0.785T_0.$$

The range of interest has $\hbar\omega$ in the visible (1.7 eV $<\hbar\omega<3$ eV), yielding

$$\Delta L=L\ln(0.54\cdot 10^{-4}T_0)\cdot 1.14\cdot 10^4/T_0, \tag{10}$$

where T_0 is in kelvins (here we average over T^{-1}); in arbitrary units,

$$\Delta L=L\ln(1.48T_0/\hbar\omega)\Delta\hbar\omega/1.32T_0. \tag{10a}$$

6. PHOTON AND ELECTRON MEAN FREE PATH. TRANSPARENCY. COOLING

The photon mean free path is $l_{\rm ph}=(n\Phi_0)^{-1}$, or, according to (1),

$$l_{\rm ph}=(n_0\Phi_0)^{-1}\exp\{\pi r^2/R_0^2\}. \tag{11}$$

The transparency can be determined on the basis of the fraction of the radiative flux passing through the cloud at an impact parameter p without being scattered:

$$\eta=\exp\left\{-\Phi_0 n_0\int_{-\infty}^{\infty}\exp[-\pi(p^2+z^2)]dz\right\}$$

$$=\exp[-\theta(p)]=\exp\{-\theta(0)\exp[-\pi p^2/R_0^2]\}, \tag{12}$$

where $\theta(0)=R_0\Phi_0 n_0$. Information about the radial distribution of intensity is only available if $\theta=\theta(0)<1$.

The electron and proton mean free path is $l_{\rm e}=(n\sigma_{\rm e})^{-1}$, where $\sigma_{\rm e}\approx 100e^4/T^2$. For $T=10^{-9}$ erg$\approx 0.7\cdot 10^7$ K,

$$\sigma_{\rm e}\approx 10^{-18}\ \text{cm}^2, \tag{13}$$

so that if $R_0/l_{\rm ph}$ is normally at most of order 1, $R_0/l_{\rm e}$ will always be much greater than 1, and $R_0\sim 10^{21}-10^{24}$ cm, $n_0\sim 10^{-3}-1$ cm^{-3}.

The cooling of x-ray clouds will usually take place essentially only via bremsstrahlung at a rate L. The rate of cooling via thermal conduction κ is

$$\frac{dQ_T}{dt}\simeq 4\pi R^2\kappa\frac{dT}{dR}\sim\frac{4\pi R_0 v_{\rm e}T_0}{\sigma_{\rm e}}. \tag{14}$$

The ratio between them is

$$\frac{L}{(dQ_T/dt)}=\frac{10^{-4}\Phi_0 R_0^2 n_0^2\sigma_{\rm e}m_{\rm e}c^2}{T_0}=10^{-4}\theta^2\frac{\sigma_{\rm e}}{\Phi_0}\frac{m_{\rm e}c^2}{T_0}, \tag{15}$$

and only occasionally will conductive cooling somewhat exceed radiative cooling.

7. QUASISTEADY LIFETIME OF AN X-RAY CLOUD

The radiation from an x-ray cloud is fueled by its contraction, i.e., by increasingly negative gravitational energy:

$$T_G=-\frac{GM^2}{\sqrt{2}R}, \tag{16}$$

and as a result of that radiation, rather than cooling down, the cloud heats up (evaporative energy losses are much smaller, while conductive losses may be comparable). Setting

$$\frac{dE_G}{dt}=\frac{GM^2}{\sqrt{2}R_0}\frac{\dot R_0}{R_0}=-L,\quad t=\frac{R_0}{\dot R_0}=\frac{GM^2}{\sqrt{2}R_0L}=3.1\frac{M}{m}\frac{T_0}{L}, \tag{17}$$

we can estimate the quasisteady lifetime to be t as given by Eq. (17).

8. EXPRESSIONS FOR N_0, S, T, AND θ IN TERMS OF THE OBSERVABLES M, T_0, L, AND R_0

We have Eqs. (2), (4), (4a), (7), and (17) with which to determine these eight quantities, as well as the definition of S as the ratio of missing mass to plasma mass. At $r_0=R_0$, this enables us to express all of these quantities in terms of the observables M, T_0, L, and R_0, and in certain instances R_0/r_0. Taking $M=(1+S)mn_0R_0^3$ [cf. (2)], $T_0=0.226GmM/R_0$ [cf. (4a)], and $L=1.25\cdot 10^{-3}\Phi_0 n_0^2R_0^3T_0^{1/2}m_{\rm e}^{1/2}c^2$ [cf. (7)], we obtain in cgs units

$$n_0=2.84\cdot 10^2L^{1/2}\Phi_0^{1/2}T_0^{5/4}G^{-3/2}m^{-3/2}M^{-3/2}m_{\rm e}^{-1/4}c^{-1}$$

$$=1.3\cdot 10^{57}L^{1/2}T_0^{5/4}M^{-3/2},$$

$$R_0=2.9\cdot 10^{-32}MT_0^{-1},$$

$$t=1.6\cdot 10^{24}MT_0L^{-1},$$

$$S=0.33m^{-5/2}G^{-3}\Phi_0^{1/2}m_{\rm e}^{1/4}cT_0^{7/4}M^{-1/2}L^{-1/2}$$

$$=1.6\cdot 10^{61}T_0^{7/4}M^{-1/2}L^{-1/2},$$

$$\theta=0.6\cdot 10^2\Phi_0^{1/2}m^{-1/2}G^{-1/2}c^{-1}m_{\rm e}^{-1/2}T_0^{1/4}M^{-1/2}L^{1/2}$$

$$=2.6\cdot 10T_0^{1/4}M^{-1/2}L^{1/2}. \tag{18}$$

A typical x-ray cloud in a cluster of galaxies may have $L\simeq 10^{44}$ erg sec^{-1}, $M=10^{46}$ g, $T_0=2\cdot 10^{-9}$ erg$=1.4\cdot 10^7$ K, so that $S\simeq 10$, $R_0\simeq 1.45\cdot 10^{23}$ cm$\simeq$50 kpc, $n_0\simeq 0.17$, and $\theta=1.7\cdot 10^{-2}$.

If the dark matter is distributed in conformity with (1), but either $r<R_0$ or a galaxy, star, neutron star, or black hole resides at the center, then (4) tells us that that R_0 will be larger at a given temperature T_0. The ratio R_0/r_0 depends on R_0, T_0, and M, and if $R_0/r_0\neq 1$, the coefficients in (18) will change.

9. THE NATURE OF THE DARK MATTER

It was shown in Refs. 1 and 2 that the hypothetical particles invoked to explain dark matter should have a mass of order 10 eV. Particles of mass $\sim$100 eV should either decay or annihilate with their antiparticles before the universe reaches critical density. Particle decay, however, is inconsistent with the existence of the solar system, and furthermore with the observed ^{235}U/^{238}U ratio, leading to too small a cosmological time $t_{\rm c}<8\cdot 10^9$ yr (see also Ref. 4). Annihilating particles should have a mass $m_\nu\gg m_{\rm p}$, and such particles would constitute most of a star's mass (indeed, if the particle products of annihilation interacted strongly with baryonic matter, the stars would explode).

Particles of mass $\sim$10 eV have a gravitational instability radius greater than that of baryonic matter. By the time of radiation decoupling from matter, $t_{\rm c}^0=10^{13}$ sec, perturbations of the photon gas [which prior to $t_{\rm c}=10^{13}$ sec is tightly bound to matter (plasma)], and thus of these same particles, which interact gravitationally with photons and matter, are necessarily no greater than $3\cdot 10^{-5}$ on scales $l>l_{\rm ph}\simeq 10^{22}$ cm. At that time, $R_{j\nu}\sim 3\cdot 10^{23}$ cm.

Perturbations cannot develop on a scale less than $R_{j\nu}$,[11] and oscillatory perturbations exist for conventional matter. Perturbations of hypothetical particles on a scale less than or equal to $R_{j\nu}$ are lacking, however, since they collide neither with one another nor with baryonic matter; the pressure concept is speculative here, at best. All perturbations are rapidly smoothed out. As long as perturbations of baryonic matter are at most of order 1, no hypothetical particles take part. From that point on, their development slows.

It is scarcely likely that this sort of dark matter could show up in x-ray clouds. In any event, despite diligent ongoing searches, no hypothetical particles that might account for the putative dark matter have thus far been detected. Before embracing exotic hypotheses, therefore, we ought to attempt to rule out inconsistencies relating to the baryonic nature of dark matter, as was done in Ref. 1. Here we also adopt the baryonic explanation for dark matter.

10. PLAUSIBILITY OF BARYONIC DARK MATTER IN X-RAY CLOUDS

According to our previous work,[1] dark matter of baryonic origin consists principally of large-scale parcels of condensed matter. The evidence provided by meteorites and asteroids[3] is that the mass distribution of particles of condensed matter looks like $f(M)\propto M^{-2}$. If the mean density of matter in the universe is $\simeq 5\cdot 10^{-30}$ g$\cdot$cm^{-3} and the mean mass of particles is 10^{-10} g, then 25% of the mass of dark matter resides in particles whose mass is less than 20 g, 50% is less than 10^{10} g, and 75% is less than 10^{23} g. Out of all photons that are absorbed, half are absorbed by particles of dark matter with mass less than 10^{-12} g, and 75% by particles of mass less than 10^{-9} g. Thus, most of the mass in dark matter is essentially unobservable optically.

The condensed matter probably consists mainly of C, N, and O, their compounds with one another and with H, and to a lesser extent Ne and heavier elements, particularly S, Si, Fe, and Mg. At the prevailing temperatures in space, $T \ll 100$ K, all are either in the solid or liquid state. Hydrogen probably constitutes $\sim$10% of all dark matter by mass (H_2O, hydrocarbons starting with CH_4, NH_3, and other compounds).

At this point, we may ask whether such dark matter can survive temperatures $\sim 10^7$ K in the plasma of an x-ray cloud. To find out, we must calculate the equilibrium temperature of a surface irradiated by bremsstrahlung and electrons at the center of the cloud.

The photon flux at the center of the cloud is

$$\begin{aligned} q_{\mathrm{ph}} &= \int_0^\infty \int_0^{\pi/2} \frac{W 2\pi r^2 dr \cos\vartheta \sin\vartheta d\vartheta}{4\pi r^2} \\ &= -\frac{1}{4}\int_0^\infty W(r)dr = \frac{\Phi_0}{274\pi} 1.15 n_0^2 T_0^{1/2} \frac{R_0 m_e^{1/2} c^2}{\sqrt{2.23}} \\ &= 0.9\cdot 10^{-3}\Phi_0 n_0^2 m_e^{1/2} c^2 T^{1/2} R_0 = 0.72 L R^{-2} \\ &= 14 L T_0^2 M^{-2} m^{-2} G^{-2} = 10^{63} L T_0^2 M^{-2}. \end{aligned} \tag{19}$$

L, M, and T_0 are assumed to be in cgs units in the very last expression. The power per unit area transferred by the electron flux is

$$\begin{aligned} q_e &= 2 T_0 n_0 \sqrt{2T_0/\pi m_e} \\ &= 0.7\cdot 10^{71} L^{1/2} T_0^{11/4} M^{-3/2} \ \text{(cgs)}. \end{aligned} \tag{20}$$

Adopting the values $L=10^{44}$, $T=2\cdot 10^{-9}$, $M=10^{46}$ as before, we obtain $q_{\mathrm{ph}}=4\cdot 10^{-3}$ erg/cm$^2\cdot$sec and $q_e=0.84$ erg/cm$^2\cdot$sec.

In this example, electrons produce most of the heating. Note, however, that the electrons do not give up all their energy—much less than that, in fact, so that the numerical code with $q_e=0.84$ erg/cm$^2\cdot$sec yields too high a surface temperature, which is obtained by setting $q_e=q_{\mathrm{ph}}=5.7\cdot 10^{-5}T^4$, where T is in kelvins (Stefan–Boltzmann law). The dark-matter particle temperature obtained is 11 K. Since we are taking a fourth root here, the particle temperature remains low over a wide range of L, T_0, and M. Thus, baryonic matter can easily exist in x-ray clouds.

We still need to assess the sputtering of dark-matter particles by protons with energy $\sim$1 keV and $n_0 \sim 1$. Proton velocities at $n_0\sim 1$ are $\sim 3\cdot 10^7$ cm$\cdot$sec^{-1}, and the sputtering coefficient is of order unity. One atomic layer, containing some 10^{15} atoms/cm^2, will erode in $\sim 3\cdot 10^7$ sec=1 yr. Since half the dark-matter particles have mass greater than 10^{10} g, containing more than 10^{10} atomic layers, more than 10^{10} yr would be required. The first to be eroded would be dust particles with masses up to 10^{-9} g, which would be destroyed in 10^4 yr. It must be borne in mind, however, that previously sputtered atoms would be recondensing on the dust particles at the same time, so that there should be no significant change in the amount of dark matter in the plasma.

11. ORIGIN OF DARK MATTER. THE FIRST STARS

We assume that at the present time, the mean density of matter in the universe is close to the critical value $\rho_{\mathrm{cr}} \cong 5\cdot 10^{-30}$ g cm^{-3}, and that it is essentially all of baryonic origin. At the present time, then, $t_c \sim (6\pi G\rho_{\mathrm{cr}})^{-1/2}=12.7$ Gyr.

By the time radiation decoupled from matter ($t_c=10^{13}$ sec), at which point the matter, due to the recombination of plasma ($T\approx 3200$ K), became transparent to photons, the minimum gravitationally unstable mass of baryonic matter was $(5\cdot 10^5 - 10^6)\, M_\odot$. (In previous work,[1,2] due to the enormous heat capacity of the photon gas, the Jeans radius was identified with the reciprocal of the gravitational instability wave number,

$$R_J = K_0^{-1} = v_s(4\pi G\rho)^{-1/2},$$

where $v_s=(T/m)^{1/2}$ is the isothermal speed of sound. The corresponding result obtained in that work was $M_j=2\cdot 10^3$ $M_\odot$. A better figure, however, is probably $R_j=2\pi K_0^{-1}$, which yields $M_j=5\cdot 10^5$ $M_\odot$.[12] That value remained unchanged as long as the temperature of the baryonic matter was approximately equal to that of the photon gas which, despite the very low degree of ionization, continued to heat the baryonic matter for a long time.

The heat capacity of the photon gas is 10^8 times that of the baryonic matter. Nevertheless, the baryonic matter ultimately cools more rapidly (in the limit as $T_{\mathrm{ph}} \ll 300$ K, $T_b=1.36\cdot 10^{-3}T_{\mathrm{ph}}^2$, with T in kelvins). The calculation was carried out as in Ref. 13, but assuming that the dark matter is baryonic and that the mean density of the universe at the present time is close to the critical value $\rho_b = \rho_{cr} = 5\cdot 10^{-30}$ $g\cdot cm^{-3}$; by contrast, it was assumed in Ref. 13 that $\rho = 10^{-31}$ $g\cdot cm^{-3}$.

Perturbations with $M < M_j = 5\cdot 10^5\ M_\odot$ cannot develop prior to $t_c = 10^{14}$ sec. The time required for small perturbations to develop in the primordial matter (12H+He) is $t > \alpha^{-3/2}\cdot 10^{13}$ sec, where α is the magnitude of the relative density perturbation $\delta\rho/\rho \sim 1$ prior to cessation of the initial Hubble expansion.

This is followed by a contraction stage and the formation of stars. If the mass of a nascent star very slightly exceeds M_j, the contraction and heating of the star may not proceed to the temperature at which nuclear reactions are ignited, nor even at which plasma is produced, and expansion may begin anew. A description of this process is outside the scope of the present paper: the theory was worked out beginning with the work of Ritter (1883), Emden (1907), and others.[14] In any event, the time for a star to form is limited at the lower range,[15] and also it should be proportional to $\alpha^{-3/2}$.

The foregoing all applies to masses greater than $5\cdot 10^5$ $M_\odot$. As for α, it has only recently become possible to detect fluctuations in the temperature of the microwave background—reaching back to $t_c = 10^{13}$ sec—at the $3\cdot 10^{-5}$ level, and only in 1992 were fluctuations detected at $\delta T/T \sim 10^{-5}$ $[\delta\rho/\rho \approx 4(\delta T/T)]$ over angular distances of 0.18°, which for $t_c = 10^{13}$ sec corresponds to linear distances of $3\cdot 10^{22}$ cm (and which is less than $R_{j\nu} = 10^{23}$ cm for $m_\nu c^2 = 10$ eV). This result is consistent with the photon mean free path for $t_c = 10^{13}$ sec. Fluctuations are obviously impossible at smaller scales. Since radiation and matter were tightly coupled at $t_c < 10^{13}$ sec, these same fluctuations also affected the density of matter.

The next question that arises has to do with just how perturbations depend on the linear size of a region or its mass. The answer is unclear—possibly as $M^{-1/2}$, possibly as $M^{-1/3}$ (nor have other possibilities been ruled out).[15] The first alternative seems more natural, but the second is somewhat more consistent with reality, inasmuch as there has been no indication of the past existence of stars with $M \sim 10^6$ $M_\odot$, and based upon other considerations as well. At $t_c = 10^{13}$ sec, the mass corresponding to l_{ph} is $M \approx 10^{43}$ g. If the corresponding perturbations were detected at a level $\alpha \sim 10^{-5}$, and if the perturbations went as $\propto M^{-1/2}$, then for a minimal Jeans mass $M_j = 5\cdot 10^5\ M_\odot = 10^{39}$ g, we might expect $\alpha \sim 1$, which would lead to a huge number of stars of that mass in the early universe, 10^{10} years ago ($t_c \approx 10^{17}$ sec). If $\alpha \sim M^{-1/3}$, then for M_j we obtain $\alpha \sim 4\cdot 10^{-2}$, although this too leads to similar stars by $t_c = 10^{16}$ sec. Perturbations probably depend on mass even more weakly. But by that time, the temperature of baryonic matter would have fallen to 3.4 K, and M_j to $2M_\odot$. This then means that somewhat earlier ($t_c = 10^8$ yr), perturbations led to the formation of stars with masses of order $\sim 100\ M_\odot$, since α would be at least 0.1 for such masses. Consequently, the first generation consisted almost entirely of massive stars ($\sim 100\ M_\odot$). Such stars would have fully evolved after $\sim 10^6$ yr, and ended their lives in a supernova explosion, contaminating the interstellar medium with heavier elements (mainly C, N, and O) primarily in the condensed state (see below). The temperature of the microwave background would have been approximately 70 K at that point.

Subsequent generations of stars would then, to a large extent, have been formed in gas and dust clouds, and would also have been more massive than the sun ($>2M_\odot$). They evolved in about 10^9 yr, and also for the most part became supernovae. After the explosion, a neutron star with $M \leqslant 1.4M_\odot$ remained.

The rest of the star's mass would be ejected into space.

For example, in SN1987A, more than 15 $M_\odot$ was ejected as dust and gas (mostly H, He, and H_2), i.e., about 90% of the star's initial mass. The expansion velocity of this shell was more than 10^9 $cm\cdot sec^{-1}$, corresponding to an initial temperature of order 10^{11} K. The assumed initial radius of the ejected shell was approximately 10^{11} cm, and its volume was 10^{33} cm^3, corresponding to an initial heavy-element concentration of $n_0 \sim 10^{24}$ cm^{-3}. The expansion velocity of the shell can be assumed constant at $v_0 \approx 10^9$ cm/sec^{-1}.

Now let the concentration fall off as R^{-3}, and the temperature as R^{-2}, where R is the mean radius of the expanding shell. We then obtain for the radius of the ball of condensed elements

$$4\pi r^2(dr/dt) = 4\pi r^2 n v_T a^3, \quad \text{or} \quad (dr/dt) = n v_T a^3,$$

where a^3 is the volume ascribed to each atom, v_T is the mean thermal velocity of the condensed elements, and n is their number density. Obviously

$$n \approx n_0(R_0/R)^3, \quad v_T \approx v_0(R_0/R),$$

so

$$\frac{dr}{v_0 dt} = \frac{dr}{dR} = \frac{n v_T a^3}{v_0} = n_0 a^3 (R_0/R)^4,$$

$$r = n_0 a^3 R_0^4 \int_{R_1}^{R_2} \frac{dR}{R^4} = \frac{n_0 a^3 R_0^4}{3R_1^3}\left(1 - \frac{R_1^3}{R_2^3}\right).$$

Taking $n_0 = 10^{24}$ cm^{-3}, $R_0 = 10^{11}$ cm, $a^3 = 10^{-23}$ cm^{-3}, and $R_1 = 10^{15}$ cm, corresponding to $T = 10^3$ K at the beginning of condensation, we obtain $r \approx 0.3$ cm.

This would all be the case if the number of condensation centers were less than 1 per 10^{22} atoms. It is in fact likely that the number is much greater, and that fine dust is formed much earlier. Almost all of the precipitable matter is exhausted, and dust grains proceed to stick together to form more massive objects, possibly in accordance with the mass distribution function of Ref. 3. Very fine grains are slowed by the interstellar gas (12H+He) and remain within the galaxy itself. Particles above $\sim 10^{-9}$ g (at a mean gas density of ~ 0.1 cm^{-3}) leave for the halo, thereby becoming dark matter. This dark matter probably then comes to thermal equilibrium with the microwave background, and subsequently heats the interstellar gas to the background temperature.

By virtue of the foregoing, most condensed matter—the missing mass—winds up in the galactic halo. Second and third generation late-type stars spawned by clouds of gas and dust (cf. Ref. 1) actually contain 80–90% heavy elements (C, N, O,...) by mass; the $\sim 2\%$ by mass observed spectroscopically would seem to be a surface effect, since the dust contracts first when a cloud of gas and dust contracts to form a star. Accordingly, the estimated lifetime of a solar-type star should probably be reduced by an order of magnitude, from $\sim 10^{11}$ yr to $\sim 10^{10}$ yr. As for the sun, this argument is favored by neutrino measurements that indicate the $p-p$ cycle ("boron" neutrinos) can account for at most 40% of the solar luminosity. The rest of the energy is derived from the Bethe CNO cycle, with perhaps another $\sim 3\%$ at the center of the sun coming from $\mathrm{He}+\mathrm{C}\rightarrow\mathrm{O}+\gamma 7.16$ MeV. Globular cluster stars, most of which reside outside the galactic disk, may be an exception. These were probably formed earlier in regions not yet contaminated by heavy elements, out of large-scale perturbations ($\sim 10^6\ M_\odot$) that fragmented at $t_c > 10^{16}$ sec, with $T_b \approx 3$ K and $M_j \sim M_\odot$.

Many unsolved problems in physical cosmology are related to the idea of baryonic dark matter or missing mass. This problem has not yielded even to suggestions of unobservable exotic particles, which, more than likely, do not exist. Solving the missing mass problem in a baryonic context instills us with a great deal of hope. In the D/H problem, for example, in addition to the sources of deuterium proposed in Refs. 1 and 2, we now have new information on deuterium production in the solar corona (and therefore other stars). Cosmic rays of stellar origin probably fragment He nuclei into deuterons and neutrons; the latter are absorbed by protons to form new deuterons, releasing characteristic 2.15-MeV γ-rays, which can then be detected by satellite-borne instruments. The evidence here seems to favor a secondary origin for deuterium in the interstellar medium. To summarize, the idea that dark matter is baryonic in nature is not inconsistent with its being detected in x-ray clouds, and would seem to provide a more attractive way of accounting for dark matter than would hypothetical unobservable particles.

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