Shedding Light on Baryonic Dark Matter

JOSEPH SILK

Halo dark matter, if it is baryonic, may plausibly consist of compact stellar remnants. Jeans mass clouds containing 10^6 to 10^8 solar masses could have efficiently formed stars in the early universe and could plausibly have generated, for a suitably top-heavy stellar initial mass function, a high abundance of neutron stars as well as a small admixture of long-lived low mass stars. Within the resulting clusters of dark remnants, which eventually are tidally disrupted when halos eventually form, captures of neutron stars by non-degenerate stars resulted in formation of close binaries. These evolve to produce, by the present epoch, an observable x-ray signal associated with dark matter aggregations in galaxy halos and galaxy cluster cores.

ELUCIDATION OF THE NATURE OF THE DARK MATTER IN galaxy halos and clusters constitutes one of the most pressing unresolved issues in astronomy. There is overwhelming evidence that at least 90%, and perhaps as much as 99%, of the universe is in some nonluminous form. From the physicist's perspective, the most natural candidate is a weakly interacting stable massive elementary particle, produced profusely in thermal equilibrium at the enormous energies attained in the very early universe, and whose relic abundance is calculable, depending primarily on the interaction strength. Remarkably, in the case of weakly interacting massive particles (WIMPS, an acronym due to M. Turner) which interact with neutrino-like strength, a critical density, $\Omega \approx 1$, remains after particle creation and annihilation ceases: here and subsequently Ω denotes the mean cosmological density in units of the critical density in an Einstein–de Sitter universe, $3H_0{}^2/8\pi G$, where $H_0 \equiv 100h$ km s^{-1} Mpc^{-1} (with $1/2 \lesssim h \lesssim$) is Hubble's constant.

Two difficulties arise. Candidate particles, while theoretically plausible, and indeed arising in such elegant theories as supersymmetry, have not yet been discovered. Moreover, the uncertainty in predicted particle mass spans more than 30 orders of magnitude, which confounds experimental searches for dark particle candidates.

In sharp contrast, several astrophysical candidates are either known or strongly believed to exist in considerable numbers, but astronomers have not hitherto succeeded in even coming within orders of magnitude or predicting their cosmological abundance. Common examples of astrophysical dark matter candidates, generically described as MACHOs, for massive compact astrophysical halo objects, an acronym due to K. Griest, are compact stellar remnants (white dwarfs, neutron stars, and black holes), ranging in mass from about 0.3 to 100 $M_{\odot}$, and substellar fragments (brown dwarfs), in the approximate mass range 0.01 to 0.1 $M_{\odot}$.

I believe that there is a reasonable possibility that the elusive dark matter consists of compact stellar remnants. My aim here is to demonstrate the plausibility of this hypothesis, and to describe experimental projects that are capable of detecting such objects. Dark halos may not be as dark as the name implies. Several arguments may be given to support the contention that compact stellar remnants are the predominant form of dark matter: they are strictly phenomenological, but nevertheless are persuasive.

Direct dynamical measurements, which include galaxy rotation curves, x-ray halos of ellipticals, supercluster infall, and cluster velocity dispersion determination are all consistent with a value for the cosmological density $\Omega_{\rm dyn} \approx 0.1$. No extant measurements unambiguously require or firmly support the inflationary universe contention that $\Omega = 1$.

The success of the theory of primordial nucleosynthesis, culminating in the measurement of three neutrino families, requires the existence of baryonic dark matter (BDM) in an amount (*1*) that may be all that is required to account for the dynamical determination of Ω.

Known candidates for baryonic dark matter include brown dwarfs, M dwarfs, and compact remnants of massive stars. For the first two of these candidates, there are strong direct constraints. The existence of even a single brown dwarf below 70 Jupiter masses has not yet been confirmed, even though existing searches for binary companions to nearby low luminosity stars are sensitive to objects with $\gtrsim$10 Jupiter masses (*2–4*), but with a narrow range of mass ratios and separations. Direct searches for halo stars in edge-on spirals eliminate M dwarfs as being the dominant constituent of halos (*5*). I do not consider supermassive black holes as serious candidates for BDM on strictly phenomenological grounds: such objects, if they exist, are rare and invariably associated with the active nuclei of luminous galaxies. Moreover, one has little understanding of how they formed. There are also dynamical arguments for rejecting them (*6*), as well as the likelihood of generating excessive diffuse background light (7).

Compact stellar remnants in the mass range 1 to 100 $M_{\odot}$ exist in considerable number, certainly formed in the outer halos of galaxies, where one sees old stars, and formed moreover during the earliest phases of galactic star formation.

The principal counterargument against BDM consisting of compact stellar remnants is strictly theoretical, and relies upon a demonstration of excessive nucleosynthetic yields (*8*). Overproduction of diffuse background light is also a potential difficulty. Neither of these arguments is invulnerable: indeed, I shall argue below that the favored BDM theory for galaxy formation generically counters these objectives. My principal new result is the description of a novel method for detecting halo BDM by means of x-ray observations.

The author is with the Departments of Astronomy and Physics, and the Center for Particle Astrophysics, University of California, Berkeley, CA 94720, and Mount Stromlo and Siding Spring Observatories, The Australian National University, Weston Creek, ACT 2611, Australia.

Theoretical Considerations

Baryonic dark matter is usually associated with primeval isocurvature fluctuations, because cosmic microwave background (CMB) constraints rule out BDM if large-scale structure arose from primordial adiabatic density fluctuations (*9*). The primeval isocurvature fluctuation spectrum is most plausibly taken to be a featureless power-law which diverges on small scales. This is usually interpreted to mean very early collapse. Of course, collapse does not occur prior to matter-radiation decoupling because linear growth is inhibited by radiation drag, and the natural scale for collapse just after the decoupling epoch at redshift $z \approx 10^3$ is the post-decoupling Jeans mass scale, namely $\sim 10^6$ to $10^7\ M_\odot$. If extensive massive star formation occurred at $z \approx 10^2$ to 10^3, any resulting signature in the diffuse background light will be redshifted to the far infrared (10 μm to 100 μm), or to even longer wavelengths if there is sufficient dust produced in the ejecta of early stars to reprocess the photons. The predicted distortion to the CMB and other components of the diffuse extragalactic background light will contribute an energy density amounting to $\Omega_{\rm excess} \approx 4 \times 10^{-3}\Omega_{\rm BDM}(1 + z_*)^{-1} \approx 10^{-6}$, where z_* denotes the redshift of primordial star formation. This amounts to roughly 1% of the CMB and is consistent with present limits on diffuse background light, but should be detectable after a year of observation with the COBE satellite if conditions conspire to result in this level of distortion occurring near the CMB peak. Consequently, BDM does not yet have an excess diffuse background light problem provided that $\Omega_{\rm BDM} \approx 0.1$.

Excessive pollution by primordial stars of their environment, with adverse implications for subsequent galaxy formation, is a more serious source of concern. The most metal-poor halo stars have abundance patterns similar to those of younger stars, demonstrating that a previous generation of massive stars, presumably with negligible (that is, $[Z] \lesssim -4$) metallicity, succeeded in polluting the protogalaxy, leaving no, or at least very few, unevolved low-mass counterparts, the fractional number amounting at most to $d\ln N/d[Z] \approx$ constant in still luminous, low-mass remnants (*10*). Of course, nucleosynthetic yields in the past could have been smaller than for conventional stars, and the only guidance comes from theoretical considerations. For example, models of primordial helium-burning intermediate mass stars $\lesssim 8\ M_\odot$ suggest that dredge-up of CNO does not occur during helium-burning, He shell flashes being suppressed (*11*) if the metallicity $[Z] \lesssim -4$. The principal contaminant in mass loss ejecta from these stars is helium, with the stars destined to form white dwarfs. More massive stars are destined to become supernovae of Type II, and it seems difficult to avoid ejection of $\sim 0.1\ M_\odot$ of Fe from a star of initial mass $\sim 20\ M_\odot$ as is observed for supernovae of Type II such as SN 1987A in the Large Magellanic Cloud.

There is a simple way to avoid this potential source of embarrassment for BDM, provided that the enriched ejecta are efficiently recycled, as I shall argue is likely to be the case in the primordial isocurvature BDM fluctuation model. Early condensation of Jeans mass clouds results in initial collapse to a virialization radius, before any dissipation plays a major role, at a density of between 10^4 and $10\ M_\odot\ {\rm pc}^{-3}$ for a formation redshift between 1000 and 100. The inferred escape velocity from these dense self-gravitating clumps is similar to that from a globular star cluster or a young galactic cluster. In such situations, star formation is relatively inefficient, the feedback of energy from massive stars by way of expanding HII regions (*12*), winds, and especially supernovae (*13, 14*) inhibiting most of the cloud from collapse. However at high redshift, conditions differ in one important respect from those in conventional star-forming regions, owing to the intervention of Compton cooling, and I shall demonstrate that this renders primordial star formation a highly efficient process. The following simple model demonstrates how this process operates.

Consider a cloud that forms predominantly massive stars, with density profile that of a singular isothermal sphere, $\rho = \sigma^2/4\pi G r^2$, where σ is the cloud velocity dispersion. A similar argument applies to the case of a uniform cloud. The cloud mass is expected to be in the range determined by considerations of gravitational instability, namely, bounded by the post-decoupling Jeans mass, and the nonlinear scale of the cloud is inferred from the normalized spectrum of primordial isocurvature fluctuations that are the generic density fluctuation mode (*15*) in a low density cosmology ($\Omega \approx 0.1$). The primordial fluctuation power spectrum is most simply taken to be a power law, $|\delta_k|^2 \propto k^n$, with $0 \gtrsim n \gtrsim -1$ constrained to fit observations of large-scale structure, in particular the pairwise galaxy correlations. Cosmic microwave background isotropy further restricts n to the range $0 \gtrsim n \gtrsim -\frac{1}{2}$. Nonlinearity occurs at epoch z on mass scale $\sim M_{\rm o}(1 + z)^{-6/(n+3)}$ for $1 + z \gtrsim \Omega^{-1}$, and $M_{\rm o} \approx 10^{13}\ (\Omega/0.1)h^{-1}\ M_\odot$, yielding the first generation of clouds with masses between $10^6\ M_\odot$ and $10^9\ M_\odot$ at $z \approx 1000$. Fluctuations that are already nonlinear at matter-radiation decoupling, and there is no reason not to expect the primordial isocurvature spectrum to contain nonlinear baryon fluctuations on small scales and indeed to contain most of the power, can first begin to collapse as Jeans mass clouds at $z \approx 1000$. Massive stars form by $z \approx 500$, after one collapse time scale and about 10^6 years have elapsed. If the clouds are predominantly gaseous, radiative cooling is initially likely to enhance dissipation, maintaining a temperature of $\sim 10^4$ K or a velocity dispersion of $\sim 10\ {\rm km\ s^{-1}}$, whereas if little dissipation occurs, as would be the case if the dominant constituents were weakly interacting particles, the resulting cloud velocity dispersion is about $1.2(1 + z)^{1/2}M_6^{1/3}\ {\rm km\ s^{-1}}$, where the cloud mass is $M_6 \equiv M/10^6\ M_\odot$.

Stars form at a rate that cannot exceed $\rho/t_{\rm ff}$, where $t_{\rm ff}$ is the cloud free-fall time. Energy input, assumed to be via supernovae but readily generalized to include other modes of energy input that scale with star formation rate, heats the cloud on time scale $t_{\rm heat} = t^2_{\rm ff} m_{\rm SN}\nu_{\rm SN}^{-1}\rho^{-1}$, where $m_{\rm SN}$ is the mass in stars that form for each Type II supernova that is produced and can be determined from the adopted stellar initial mass function, and $\nu_{\rm SN}$ is the 4-volume of a supernova remnant that expands into an initially uniform medium, forming a cooling shell that snowplows until halted by the ambient pressure. A network of interacting shells is generated containing low density hot interstellar gas at $T \approx 10^6$ K that permeates the entire cloud and erodes colder gas fragments, as in the three-component model of the interstellar medium (*16*). If $t_{\rm heat} < t_{\rm ff}$, a wind ordinarily is driven from the cloud (*14*) that results in ejection of most of the cloud gas before it can be recycled into successive generations of massive stars. This occurs if the escape velocity is less than $\sim 60\ {\rm km\ s^{-1}}$.

The situation changes dramatically at high redshift, however, where I now argue that Compton cooling effectively quenches the wind, by cooling the shell interiors to a sound speed that is substantially below the escape velocity, and by rendering the shell motions highly supersonic, and hence highly dissipative. A stable wind cannot develop in this situation when the cooling time scale is less than the minimum of either the flow time-scale or the heating time scale evaluated at the sonic radius (*17, 18*). The Compton cooling time-scale for the ionized low density medium, $\frac{3}{4}m_{\rm e}(c\rho_\gamma\sigma_{\rm T})^{-1}$, where $c^2\rho_\gamma$ is the energy density in the CMB at redshift z, $T = 2.74\ (1 + z)K$, and $\sigma_{\rm T}$ is the Thomson cross-section, is less than $t_{\rm heat}$ at $z \gtrsim z_{\rm comp} \equiv (3m_{\rm e}\nu_{\rm SN}\rho/4\sigma_{\rm T}c\rho_{\gamma{\rm o}}t_{\rm ff}{}^2 m_{\rm SN})^{1/4} \approx 100M_6{}^{-1/4}$. To allow star formation to proceed, I also require that Compton drag must be ineffective (*19*): this is the case in the clouds provided that the cloud contraction time $t_{\rm contr}$ is less than the Hubble time $t_{\rm H}$. With $t_{\rm contr} = t^2{}_{\rm ff}/t_{\rm drag}$, where the Compton drag time scale $t_{\rm drag} = \frac{m}{m_{\rm e}}t_{\rm comp}$, and $t_{\rm H} = \frac{2}{3}H_{\rm o}{}^{-1}\Omega^{-1/2}(1+z)^{-3/2}$, one requires the epoch of primordial star formation to satisfy $z \lesssim z_* \equiv (m_p/2H_o\sigma_T c\rho_{\gamma o}t_{ff}^2\Omega_o^{1/2})^{2/11} \approx 120n^{2/11}$, where $n \approx 40\sigma^6{}_{10}\, M_6{}^{-2}$, for a cloud with velocity dispersion $\sigma_{10} \equiv \sigma/10$ km s^{-1}. I conclude that star formation proceeds efficiently at high redshift if $z_{\rm comp} \gtrsim z_*$, namely, in clouds of mass 10^6 to 10^8 $M_\odot$, no wind occurring because of the effective cooling.

Not all of the intergalactic medium collapses into clouds, however. The uncondensed mass fraction at $z \sim z_*/2$ is the reservoir for later formation of luminous matter in galaxies. Energetic photons leak out of the star-forming clouds and ionize the uncondensed intergalactic medium. One important consequence is that Compton drag prevents collapse of Jeans mass scales in the intergalactic medium, and conventional galaxy formation cannot commence, until $z \gtrsim 50x^{-0.4}(\Omega/0.1)^{0.2}$, where x is the ionized fraction. Once Compton drag is released, the relatively complex hierarchy of ensuing structure formation should ensure that the star formation will be inefficient and maintain a globally subdominant gas fraction until the deep potential wells of massive galaxies have formed by $z \sim 10$ to 30. A second consequence is that the ionization results in scattering of CMB photons, and destroys relic anisotropies on angular scales up to several degrees, corresponding to the angle subtended by the horizon at last scattering. Secondary fluctuations are generated on small (less than 1 arc minute) angular scales, but these are of smaller amplitude (*20*).

An acceptable star formation efficiency requires recycling of much of the debris from stellar ejecta into several successive generations of massive star formation in dense clouds to form the desired BDM. It is this assumption that is the most ad hoc feature of the present model. Consequently, the inferred instantaneous ionizing photon flux is much lower than postulated in earlier discussions of ionization by Very Massive Objects (*7*). Indeed, the most massive globular clusters, such as ω Cen and 47 Tuc, show clear evidence in the form of metallicity gradients that such recycling must have occurred during their formation.

Evidence does exist in regions of unusually elevated star formation for a flattened or "top heavy" initial mass function (IMF) (*21*). While some starburst galaxies show no evidence for an abnormal IMF, many interacting galaxies that are undergoing starbursts do show such indications as unusually weak Balmer absorption lines, anomalously high luminosity-to-mass ratios, and emission line characteristics that favor an interpretation invoking a preponderance of massive stars relative to the solar neighborhood IMF. This can be accommodated either by flattening the IMF, or by truncating it below ~5 to 10 $M_\odot$. There is every reason to believe that primordial star formation occurred in clouds that were strongly interacting with one another, and the phenomenology of starbursts suggests that primordial star formation most likely occurred with a suitably top-heavy IMF. There must have been relatively few stars below ~5 $M_\odot$ in the BDM-forming clouds, in order to recycle the stellar ejecta sufficiently rapidly and efficiently, and thereby produce suitably dark BDM. One could not tolerate many stars of mass below 2 to 3 $M_\odot$, and this could have been achieved either by truncating or flattening the primordial stellar IMF. Truncation seems the least likely of these alternatives, since some solar mass stars evidently formed with $[Z] \lesssim -4.0$.

One may speculate that the potential well depth discriminates between a normal and a top-heavy IMF: for example, the gas density and pressure appear to be exceptionally high in the starbursting interior of M82 (*22*) where the IMF is dominated by stars of around 20 $M_\odot$ (*23*). Cloud turbulent velocities, as measured by molecular line widths, increase as the massive star formation rate increases, and if self-gravity plays an important role in cloud support, as seems likely, these velocities provide empirical evidence that massive star formation is favored by deeper gravitational potential wells. Turbulence may also regulate protostellar outflows, which are believed to play a central role in star formation physics. For example, models for bipolar flows commonly postulate that a convective, differentially rotating, magnetized protostellar core or accretion disk is a necessary prerequisite to tapping the gravitational potential energy that must power these ubiquitous outflows, which demarcate the earliest observed stages of protostars and are believed to be responsible for halting the accretion from the ambient molecular cloud (*24*). However primordial clouds have high accretion rates (*25*) onto forming protostellar cores: an enhanced accretion rate $\sim \Delta V^3/G$, (where ΔV is the generalized sound or turbulence velocity), tends to quench convection and thereby may inhibit the generation of a sufficiently vigorous protostellar outflow (*26*), allowing predominantly massive stars to form.

Contrary views with regard to the fate of protoclouds have been expounded in the past, ranging from fragmentation into brown dwarfs to coherent collapse into a single supermassive object (*27*). My principle motivation for rejecting such arguments is only phenomenological. It is unfortunate that, from a theorist's perspective, one can say very little about the expected fate of a collapsing primordial cloud: for example, the issue of whether the lack of heavy elements helps (via opacity) or hinders (via cooling) fragmentation is largely unresolved insofar as realistic nonuniform, nonspherical collapses have not been studied over the wide dynamic range required to answer these questions.

Hence it is at least plausible, if not even likely, that BDM formed as compact remnants via efficient recycling of stellar ejecta in dense clouds, similar in mass and density to the most tightly bound globular clusters, and, simultaneously, some low mass stars formed. Clearly, the BDM IMF must be flat enough so that restrictions on the halo luminous star content, equivalent to $M/L_v \gtrsim 2000$ in spirals, are satisfied. The IMF is assumed to steepen from $x \sim 0$ ($d\ln N/d\ln M = -1 - x$) in the BDM-forming primordial clouds at $z \sim 1000$, perhaps typical of star-forming regions, to $x \gtrsim 1$ when the oldest surviving stars in galactic spheroids form in substantial numbers at $z = 10$ to 30.

Detectability of Baryonic Dark Matter

This history of BDM leads to a noteworthy observable implication. At the high star density that must inevitably have been present in the BDM-forming clouds, of order 10^4 $M_\odot$ pc^{-3} within a half-mass radius, and presumably much higher in the cloud cores, collisions between neutron stars and main sequence stars were inevitable. Some of these collisions result in tidal capture, by a process known to have occurred in globular clusters. These captures produce both x-ray binaries and millisecond pulsars as a consequence of the evolution of, and mass transfer from, the nondegenerate companions, the abundances of which are strongly enhanced in globular clusters relative to the disk and bulge. A high (primordial?) abundance of neutron stars is probably required to account for the observed frequency of recycled (millisecond) pulsars in globular clusters: these form at a rate that is about two orders of magnitude higher than can be accounted for by evolution of the observed x-ray binaries (*28*). Even if the lifetimes of x-ray binaries are overestimated in this comparison, one can still argue that the recycled pulsars, most of which are low mass binaries, are the evolutionary descendants of x-ray binaries, but the abundance problem still remains. One could understand the high abundance of neutron stars if globular clusters contain a substantial fraction of their mass (of order 10%) in neutron stars, rather than the 1 or 2% that is inferred from a conventional IMF. Other explanations are possible: for example, I have ignored capture of neutron stars by primordial binaries, a process which is likely to dominate tidal captures in present-day globulars (29), but is unimportant in the neutron-star dominated situation being discussed here. Such a high abundance of neutron stars in population II is an inevitable consequence of the BDM hypothesis that is being advocated here.

It follows that BDM, as defined here to consist primarily of neutron stars and white dwarfs with a sparse interleaving of nondegenerate stars, must inevitably have formed both x-ray binaries and recycled neutron stars. The last captures would have occurred $\sim 10^{10}$ years ago, but, as in the globular clusters, the delayed trigger of the red giant evolution of the solar mass companion means that a considerable number of binary millisecond pulsars and of x-ray binaries will be present today in the BDM. I shall concentrate here on the observable signature associated with the x-ray binaries, which are known to be very luminous, typically radiating at perhaps 10% of the Eddington luminosity or $\sim 10^{37}$ erg s^{-1}. The predicted formation rate of x-ray binaries is $\sim n_{\rm ns}\, n_* \,\langle \sigma v\rangle$, where $n_{\rm ns}$ is the number density of neutron stars in the compact BDM cluster, n_* is the number density of nondegenerate low mass stars, σ is the cross-section for capture of the neutron stars by the main sequence target star, and v is the velocity dispersion within the BDM cluster, all of this referring to conditions at $100 \lesssim z \lesssim 1000$. For illustrative purposes, I assume that a close approach, by the neutron star to within a distance d of less than three radii of the nondegenerate target star, leads to tidal capture and binary formation, and use a ratio for n_* to $n_{\rm ns}$ that saturates the upper limit on halo light from edge-on spirals at 2 to 3 Holmberg radii: for $\langle m_* \rangle = 0.3\, M_\odot$, approximately appropriate to the solar neighborhood IMF, one infers $n_*/n_{\rm ns} \sim 10^{-2}$. This leads to the estimate (30) that $\sim 10^{-13}(n_{\rm ns}/10^{-3}{\rm pc}^{-3})[(n_*/n_{\rm ns})/0.01][(m_* + m_{\rm ns})/M_\odot]\,(3R_*/d)(50$ km s$^{-1}/v)$ x-ray binaries form per dark cluster per year.

For a galaxy halo of $10^{12}\, M_\odot$, there are $\sim 10^4$ binaries that form in the $\sim 10^6$ BDM clusters over their $\sim 10^8$ year gestation period before being incorporated into a massive dark halo. The clusters subsequently suffer considerable tidal disruption because of interactions with the disk and bulge. Not all of these captured neutron stars need lead to x-ray binaries; depending on how one interprets the globular cluster statistics, only $\sim 1\%$ could attain this fate. There are other alternatives for forming recycled pulsars, the most attractive being mass transfer onto a captured white dwarf, and then accretion-induced collapse forming a neutron star (31). Hence, the predicted number of x-ray binaries per BDM halo is in the range 10 to 10^3. Moreover, the lifetime of the x-ray binary phase may be as short as 10^7 years or as long as 10^9 years, with the shorter lifetime providing the most attractive interpretation of the statistics (32). This results in $L_x/M \sim 10^{-5}$ to 10^{-7}, if 10% of the x-ray binaries radiate at the Eddington luminosity.

A value of $L_x/M \sim 10^{-7}$ is probably consistent with x-ray observations of our own galaxy, implying the presence of ~ 1 to 10 x-ray binaries associated with halo dark matter. Many other galaxies have higher x-ray luminosities, and especially if $L_x/M \sim 10^{-5}$, the possibility arises that a substantial part of the observed x-ray flux could be due to x-ray binaries associated with the halo BDM. Spectroscopic evidence favors an appreciable x-ray binary contribution, and the correlation between x-ray and blue luminosity suggests that there may be two distinct types of x-ray sources involved, to account for the observed change in slope. Halo binaries provide a possible explanation for a substantial fraction of the x-ray fluxes detected from the most luminous galaxies with $L_x \approx 10^{40}$ ergs^{-1}.

The binary frequency is expected to scale with spheroid luminosity, since it depends both on the halo luminous star density as well as on the neutron star density. Thus the x-ray luminosity from elliptical galaxy halos should be much higher than for spirals. Indeed, this leads to an alternative explanation for the x-ray fluxes observed from elliptical galaxies. Rather than attribute the diffuse x-ray flux to emission from cooling flows, which in the more extreme cases cannot be interpreted without invoking a suitably unobservable sink, in the form of low mass stars, for the gas, one might consider that x-ray binaries are responsible for the observed fluxes. In galaxy cluster cores, which contain $\sim 10^{15}\, M_\odot$ of dark matter, one can plausibly attain excess x-ray luminosities, relative to the thermal bremsstrahlung from the intracluster gas, as high as $\sim 10^{10}\, L_\odot$. Such excess x-ray luminosities are observed in up to ~ 20 percent of Abell clusters (33), the present interpretation requiring $L_x/M \sim 10^{-5}$ with the implication that L_x/M attains this value only in the halos of ellipticals. The more efficient neutron star formation in this case would inevitably involve more heavy element production, and a natural consequence is that the near-solar metallicity measured for intracluster gas originates as unrecycled ejecta from the primordial BDM clusters. Furthermore, one would expect the metallicity to track L_x/M, suggesting that in spirals, the associated protogalactic gas had a seed enrichment about one percent of that indirectly inferred for ellipticals from the intracluster gas, or about ~ 0.005 of solar abundance. This is similar to what is observed in extreme Population II. Those few stars in the halo with much lower abundances of heavy elements could have formed from relatively rare pockets of pristine gas.

One can readily imagine how such a situation might arise: for example, ellipticals are found, on the average, in denser environments than spirals, and denser BDM clusters could form as a consequence of the initial conditions, with large-scale power modulating and boosting the fluctuations on sub-galactic scales. One might therefore, anticipate that the internal density of the clumps that formed elliptical BDM was higher, the clumps condensing somewhat earlier, than for spiral BDM. A boost of $n_{\rm ns}$ by an order of magnitude would be achieved for a factor of 2 modulation in peak amplitude, assuming Gaussian fluctuations, in a simple top-hat collapse model. One consequence would be that ellipticals have denser, more compact halos than spirals, an effect for which evidence has been cited both on observational (34) [but see also Hernquist and Quinn (35)] and theoretical (36) grounds. Moreover, similar modulation effects could, at a later stage, account for the differences in protogalactic star formation rates and efficiencies between ellipticals and spirals. A specific prediction of such a model for excess x-ray emission observed from ellipticals and cluster cores would be that the x-ray luminosity should correlate with the mass of dark matter, and should spectroscopically resemble emission from x-ray binaries rather than have a characteristically thermal bremsstrahlung spectrum.

Conclusions

I have argued that halo dark matter, if it indeed is BDM, is likely to initially consist of clusters of compact stellar remnants. These clusters are sufficiently dense and long-lived that binary captures occur of neutron stars by the few nondegenerate stars that must also have formed from a suitably top-heavy IMF. After 15×10^9 years, the continuing evolution of these binaries produces x-ray binaries that, at least collectively, may result in a substantial diffuse x-ray flux especially from elliptical galaxy halos.

There are additional compact binary signatures of interest. The final merging of neutron star binaries results in a potentially detectable burst of gravitational radiation. The present interpretation of BDM suggests that the predicted frequency of such bursts that occurred in the early stages of halo formation as well as throughout the history of the universe will exceed that expected from characteristic Population II objects by an order of magnitude or more.

White dwarfs are also likely to have been produced in considerable numbers. Both mergers of white dwarf binaries and mass transfer onto a close white dwarf companion can result in formation of Type I supernovae in galaxy halos. Some of the wide binaries that evolve into white dwarf pairs result in supernovae at a level that is potentially detectable (*37*), and accretion-induced collapse of white dwarfs, a process invoked to account for recycled pulsars, also would be a source of supernovae. Direct detection of halo white dwarfs is also feasible. Provided that the halo formed no more than 6×10^9 years prior to the disk, halo white dwarfs are still sufficiently luminous ($L \gtrsim 10^{-5}$ to $10^{-6}\ L_\odot$) to be detectable in the solar vicinity by direct searches for faint high velocity stars (*38*).

Direct searches will also provide a useful constraint on any substantial brown dwarf component of the halo. Brown dwarfs are conjectured to span the mass range between the hydrogen burning limit ($\sim 0.1\ M_\odot$ for primordial composition) and the fragmentation limit ($\sim 0.01\ M_\odot$, in opacity-limited dynamical fragmentation). Objects at the upper end of this mass range will remain luminous for a Hubble time, and it should be feasible to do a wide-area near-infrared search for the nearest such objects.

The most comprehensive direct detection experiment should be capable of detecting a broad range of generic MACHO candidates. It involves searching for the gravitational microlensing signal, with predicted probability per event (*39*) of order 10^{-6}, by monitoring several million stars in the Large Magellanic Cloud. The predicted time scale (in years) for the characteristic time-symmetric achromatic signal arising whenever a compact object of mass M_x enters the Einstein cone towards a background star is $\sim 0.2(M_x/M_\odot)^{1/2}$.

Finally, I address a dynamical consequence of the interaction of halo BDM in the form of primeval clusters with galactic disks and spheroids. Tidal shocking will destroy most of these clusters in the inner galaxy, but will also result in considerable heating of the old disk. There is no fully satisfactory explanation for the thickness of the galactic disk which also accounts for the local velocity ellipsoid, the age dependence of the velocity dispersion, and the radial dependence of the disk scale height (*40, 41*). The most successful conventional model relies on a combination of heating by massive molecular clouds and transient spiral waves (*42*), although the stability of the inner disk to local gravitational instabilities (*43*) makes the latter effect questionable.

Disk heating by dark clusters in galaxy halos provides a speculative but attractive resolution of several of the difficulties with earlier models (*44*), provided that the cluster parameters are constrained to values (core radius ~ 1 pc, mass ~ 10^6 to $10^7\ M_\odot$, compact remnant masses ~ $10\ M_\odot$) that arise naturally in the present model. The cluster masses may have to lie closer to the upper end of this mass range, otherwise they may not produce sufficient disk heating, because cluster lifetimes in the inner galaxy may be substantially less than the age of the disk. A study of the related problem of the dynamical evolution of the globular cluster system found (*45*) that the clusters are disrupted by bulge shocking in the inner galaxy. The clusters do not survive within a galactocentric distance of ~2 kpc, and hence will not be dragged into the galactic nucleus by dynamical friction, a difficulty encountered in massive black hole models for BDM (*6*). Implications for the radial profiles of disk velocity dispersion and scale length, predicted to vary as $\sigma_d^2 \propto Dt$ and $H \propto \sigma_d^2/\mu_d$, where the diffusion coefficient $D \approx G^2 M_{cl}\rho_h/\sigma_h$, are complicated by the time-dependent tidal disruption of the inner clusters.

One potentially interesting signature involves the chemical abundances and dynamical characteristics of the so-called thick disk, since it is primarily the oldest disk stars that are heated by dark halo clusters. Because of tidal disruption of the inner dark clusters, the intermediate and young disk, which dominate the total disk light, will be heated to a much lesser extent by this mechanism. The radial dependence of the velocity dispersion of the old disk is expected to vary as ~ $(\rho_h)^{1/2}$ at a galactocentric distance in excess of about 2 kpc. The inferred variation in scale height is possibly detectable between this radius and the radius out to which the disk is still self-gravitating, about 8 kpc, the scale height varying as $\rho_h e^{\alpha r}$, for a disk of scale-length $\alpha^{-1} \approx 4$ kpc. One cannot directly compare this prediction with observations of a constant disk scale-height out to 4 to 5 disk scale-lengths (*46*) which apply over this radial range but include an admixture of young and old disk components. Another approach relies on observations of the local thick disk (*47*), which contains ~1% of disk stars, but whose existence as a kinematically or chemically discrete component of the galaxy is controversial. Observations of the thick disk may eventually be able to search for the expected increase in vertical velocity dispersion at decreasing galactocentric radius.

REFERENCES AND NOTES

1. K. A. Olive, D. N. Schramm, G. Steigman, T. P. Walker, *Phys. Lett.* B, in press.
2. B. Campbell, G. Walker, S. Yang, *Astrophys. J.* **331**, 902 (1988).
3. G. W. Marcy and K. J. Benitz, *ibid.* **344**, 441 (1989).
4. T. J. Henry and D. W. McCarthy, *ibid.* **350**, 334 (1990).
5. M. F. Skrutskie, M. A. Shure, S. Beckwith, *ibid.* **299**, 303 (1985).
6. C. G. Lacey and J. P. Ostriker, *ibid.*, p. 633.
7. B. J. Carr, J. R. Bond, W. D. Arnett, *ibid.* **277**, 445 (1984).
8. D. Ryu, K. A. Olive, J. Silk, *ibid.* **353**, 81 (1990).
9. J. Silk, *Ann. N.Y. Acad. Sci.* **571**, 44 (1990).
10. T. C. Beers, G. W. Preston, S. A. Shectman, *Astron. J.* **90**, 2089 (1985).
11. M. Fujimoto, I. Iben, A. Chieffi, A. Tornambe, *Astrophys. J.* **287**, 749 (1984).
12. A. Noriega-Crespo, P. Bodenheimer, D. N. C. Lin, G. Tenorio-Tagle, *Mon. Not. R. Astron. Soc.* **237**, 461 (1989).
13. R. B. Larson, *ibid.* **169**, 229 (1974).
14. A. Dekel and J. Silk, *Astrophys. J.* **303**, 39 (1986).
15. P. J. E. Peebles, in *The Early Universe*, W. G. Unruh and G. W. Semenoff, Eds. (Reidel, Dordrecht, 1988), pp. 203–214.
16. C. McKee and J. P. Ostriker, *Astrophys. J.* **218**, 148 (1977).
17. W. G. Mathews and J. Baker, *ibid.* **170**, 241 (1971).
18. J. N. Bregman, *ibid.* **224**, 768 (1978).
19. C. Hogan, *Mon. Not. R. Astron. Soc.* **185**, 889 (1978).
20. E. Vishniac, *Astrophys. J.* **322**, 597 (1987).
21. J. Scalo, in *Windows On Galaxies*, A. Renzini, G. Fabbiano, J. S. Gallagher, Eds. (Kluwer, Dordrecht, in press).
22. J. B. Lugten *et al. Astrophys. J.* **311**, L51 (1986).
23. P. J. Puxley *et al.*, *ibid.* **345**, 163 (1989).
24. C. Lada, *Annu. Revs. Astron. Astrophys.* **23**, 267 (1985).
25. S. W. Stahler, F. Palla, E. E. Salpeter, *Astrophys. J.* **302**, 590 (1986).
26. J. Silk, in *The Physics and Chemistry of Interstellar Molecular Clouds*, G. Winnewisser and T. Armstrong, Eds. (Springer-Verlag, Berlin, 1989), pp. 285–296.
27. M. J. Rees, in *Formation and Evolution of Galaxies and Large Structure in the Universe*, J. Audouze and J. Tran Thanh Van, Eds. (Editions Frontieres, Gif-sur-Yvette, 1984), pp. 239–252.
28. S. R. Kulkarni, R. Narayan, R. W. Romani, *Astrophys. J.*, in press.
29. P. Hut, B. W. Murphy, F. Verbunt, *Astron. Astrophys.*, in press.
30. F. Verbunt, in *Timing Neutron Stars*, H. Ogelman and E. J. P. van den Heuvel, Eds. (Kluwer, Dordrecht, 1989), pp. 593–608.
31. J. Grindlay and C. Bailyn, *Nature* **336**, 48 (1989).
32. R. W. Romani, *Astrophys. J.*, in press.
33. C. Jones and W. Forman, *ibid.* **276**, 38 (1984).
34. L. Hernquist and P. J. Quinn, *ibid.* **312**, 1 (1987).
35. ———, *ibid.* **331**, 682 (1988).
36. W. H. Zurek, P. J. Quinn, J. K. Salmon, *ibid.* **330**, 519 (1988).
37. T. Smecker and R. F. G. Wyse, *ibid.*, in press.
38. C. Tamanaha, J. Silk, M. Wood, D. Winget, *ibid.* **358**, 164 (1990).
39. B. Paczynski, *ibid.* **304**, 1 (1986).
40. C. G. Lacey, *Mon. Not. R. Astron. Soc.* **208**, 687 (1984).
41. R. Wielen and B. Fuchs, in *The Milky Way Galaxy*, H. van Woerden, R. J. Allen, W. B. Burton, Eds. (Reidel, Dordrecht, 1985), pp. 481–490.
42. R. J. Carlberg, *Astrophys. J.* **322**, 59 (1987).
43. J. Lewis and K. C. Freeman, *Astron. J.* **97**, 139 (1989).
44. B. J. Carr and C. G. Lacey, *Astrophys. J.* **316**, 23 (1987).
45. L. Aguilar, P. Hut, J. P. Ostriker, *ibid.* **335**, 720 (1988).
46. P. C. van der Kruit and L. Searle, *Astron. Astrophys.* **110**, 61 (1984).
47. G. Gilmore, R. F. G. Wyse, C. Kuijken, *Annu. Revs. Astr. Astrophys.* **27**, 555 (1990).

48. I am grateful to A. Rodgers for providing a hospitable and stimulating environment at Mount Stromlo during the writing of this article. My research has been supported at Berkeley in part by grants from NASA and NSF.