DARK POPULATIONS

Joseph Silk
Departments of Astronomy and Physics, and Center for Particle Astrophysics, University of California, Berkeley

ABSTRACT

After summarizing the evidence for dark baryonic matter in various environments, I review theoretical considerations relevant to the nature of such a component of the universe in regions where it is the dominant mass fraction. Phenomenological constraints are given on the primordial stellar initial mass function. The primordial rate of star formation is evaluated during the early stages of galaxy formation, utilizing simple theoretical considerations motivated by present day star formation rates. Applications are given to predominantly dark objects whose existence is inferred from galaxy formation theory, including low surface brightness giant and dwarf galaxies. Prospects for detection of dark populations that dominate our own galactic halo are described.

1. INTRODUCTION

Dark baryonic matter is an inescapable part of astronomical life. While negligible on the scale of the solar system, the local disk may contain a substantial dark component. Perhaps coincidentally, old stellar populations in galaxy spheroids and in ellipticals may contain a similar fractional component of dark matter. It is tempting to argue by continuity that regions where larger fractional amounts of dark matter are found, including galaxy halos and dE galaxies, which also consist almost exclusively of old stars, contain dark matter that is of essentially the same composition as that found elsewhere. Arguments of this type, treating dark matter as simply an extreme variation on the content of known, usually old, systems, will be developed here. It is of course possible that the dark matter content of dark halos consists of some qualitatively new population or even form that does not appear in luminous systems. Indeed I regard this possibility as likely for the uniform dark matter component postulated to give a critical closure density for the universe. However, nature would surely have to be perverse were the dark matter associated with luminous matter to drastically change its form as the dark matter content of a stellar system increases over a modest range.

This article is organized as follows. Section 2 summarizes the dark matter fraction in various astronomical systems, where I take dark matter to include any dark population whose presence is inferred from dynamical measurements. Sections 3 and 4 present various constraints from theory and from phenomenology on the initial mass-function of primordial stars that would have formed a baryonic dark halo. Heuristic expressions are given in Section 5 for the primordial star formation rate. Section 6 presents applications of the foregoing theory to dark systems expected in the context of models for the large-scale structure of the universe. The current status of searches for baryonic dark matter in our halo is reviewed in Section 7.

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2. OBSERVED DARK MATTER FRACTION

A conservative estimate of the dark mass fraction in the solar system would be less than 0.1 percent. There is little support in our immediate vicinity for the contention that a substantial fraction of the dark mass might be in the form of planets, presumably Jupiter-like because of its hydrogen-rich composition. Moreover, the formation of Jupiter would be questionable in the absence of a rocky core.

In the old galactic disk, at least 10 percent of the mass is in the form of white dwarfs and neutron stars which accordingly may be considered as dark matter candidates. Only the very nearest cold white dwarfs (within a few parsecs of the sun) are detectable, and the old neutron stars are visible as radio pulsars, x-ray binaries, or perhaps gamma-ray bursters if they undergo substantial accretion. The white dwarf fraction comes from direct observation of the nearby white dwarf luminosity function, but would undercount white dwarfs with a large scale height. The neutron star (and black hole) fraction is estimated by assuming a past star formation rate in the disk, and is uncertain but likely to contribute considerably less than white dwarfs to the dark mass fraction.

An alternative approach to detecting the disk dark matter density near the sun relies on measuring the local gravitational acceleration perpendicular to the galactic plane. This has not led to any definitive result with regard to the need for a component of dark matter that is in excess of the known contributions from compact stellar remnants, gas and stars[1]. Up to fifty percent of the disk could be in dark matter without producing any excessive acceleration, and at least one analysis[2] has provided evidence for such a contribution. However uncertainties in the distribution and kinematics of the stellar populations used in the dynamic analyses[3] mean that the disk dark matter fraction satisfies $0.1 \leq f \leq 0.5$.

Globular clusters, as the oldest stellar population in the galaxy, would be a good laboratory for investigating the dark matter content of stellar populations were it not for the bias introduced by dynamical relaxation. Objects less massive than $1M_{\odot}$ tend to evaporate, and more massive objects sink to the center. In the latter case, the observed distribution and dynamics of globular cluster stars provide a sensitive probe of the dark matter content. Modelling suggests a primordial neutron star mass fraction of between 0.1 and 1 percent, although white dwarfs could constitute up to 30 percent of the globular cluster mass in well-studied examples[4]. Binary formation, mass transfer, and stellar mergers are believed to be a continuing source of massive star formation in the cases of such globular clusters as 47 Tuc, where there are at least 12 millisecond pulsars as well as a centrally concentrated population of blue stragglers.

Modelling of the galactic spheroid results in about as much uncertainty as there is in the disk with regard to a possible dark matter component[5,6]. The situation should improve when the OH/IR stars are incorporated into the dynamical modelling. A similar uncertainty, allowing up to fifty percent of the dynamically measured mass to be dark, applies to elliptical galaxies within their characteristic half-light radii r_e. The mass-to-light ratio $M/L_B \approx 10h$, where $h = H_0/100$ km s^{-1}Mpc^{-1}, corresponds to that of an old stellar population which is normalized relative to the stellar population of the solar neighborhood. Our local mass-to-light ratio is between 2 and 4, and reflects the uncertainty in the contribution of local dark matter. One may conclude that, within the uncertainties, there is no dark matter problem in the luminous regions of galaxies, provided that one is prepared to tolerate the possibility of an initial mass function that results in up to fifty percent of the mass consisting either of compact stellar remnants or, less plausibly, brown dwarfs. Brown dwarfs have lower likelihood, in my view, because the required extrapolation from known dark matter contributions to well-studied regions is much larger than for white dwarfs. There is as yet no unambiguous evidence for the existence of even a single brown dwarf[7]. On larger scales, rotation curve measurements reveal that luminous spirals are embedded in dark halos that extend to more than 2–3 Holmberg radii. The dark mass fraction within this distance, which is only as far as the dark matter can be studied, exceeds 80 percent of the total enclosed mass. A similar result is believed to apply to ellipticals, although the evidence is far sparser, being based on rare cases of 21 cm rotation curves and a somewhat model-dependent interpretation of the x-ray luminosity as emission from diffuse hot gas that traces the halo potential well. Nearby dwarf ellipticals have also been the subject of intensive study, and these low surface brightness systems are dominated even in their central regions by dark matter. In these latter objects, the dark mass fraction amounts to about 90 percent for the extreme cases (where $M/L_B = 50 - 100$). A similar fraction is measured in galaxy clusters, where $M/L_B \approx 300h$, and about 10 percent of the mass is in diffuse hot gas.

An immediate reaction to the observed dark matter fraction in the regions (large-scale and dE's) where it is most extreme is that only a very modest extrapolation by about a factor of 3 (modest by astrophysical standards!) is required if the *entire* dark mass were to consist of white dwarfs rather than be characterized by the solar neighbourhood content of roughly 30 percent. A second reaction is that 90 percent is very different from the 99 percent dark fraction required for an inflationary universe, for which $\Omega = 1$, where we can write the ratio of mass to luminosity density in terms of Ω as $\Omega = (M/L_B)/(1500h)$. Thirdly, the success of the primordial nucleosynthesis model, combined with the LEP measurement of 3 neutrino species, in accounting for the abundances of ^{4}He, ^{2}H and ^{7}Li requires a substantial amount of baryonic matter in excess of that seen in luminous galaxies. Translating the limit $\Omega_b h^2 = 0.015$ into dark baryonic fraction f implies $0.3 \lesssim f \lesssim 0.8$. If this matter is in galaxy halos, then it cannot be diffuse gas: however, diffuse hot intergalactic gas can readily accomodate a density $\Omega \lesssim 0.1$ without producing an excessive x-ray background. Inhomogeneities generated at the quark- hadron phase transition can lead to deviations from the standard, homogeneous model predictions of light element abundances that allow a larger value of Ω_b. A factor of 2 increase in Ω_b cannot easily be excluded, so that $\Omega_b \lesssim 0.1$ and $f \lesssim 0.9$, with the upper limits possibly even being *required* by the nucleosynthesis modelling. Indeed, a recent analysis of lithium depletion via convection and diffusion in population II stars finds that $\Omega_b h^2 = 0.046$ is allowed, and possibly even favoured, by the observed dispersion in reddening-corrected ^{7}Li equivalent widths in metal-poor halo stars[8].

Thus I conclude that *all* of the dark matter that is directly *measured* may necessarily be baryonic. Since this is the dark matter that is associated with galaxies, either in halos or in clusters, such a conclusion is not very radical. Weakly interacting particle dark matter, a favored if controversial relic from the Big Bang because of the lack of any existence proof, is more likely to be associated with the relatively uniform dark matter distribution that is required in order to account for a critical density of matter $3H_0^2/8\pi G$ if the universe is bound or marginally bound.

3. BARYONIC DARK MATTER

Many candidates exist for baryonic dark matter (BDM) that range in mass from cometary scales to supermassive black holes. One can be confident that BDM formed from gas with zero metallicity at high redshift, and most likely in clouds of subgalactic mass. The successful bottom-up approach to large-scale structure via N-body simulation modelling of the galaxy correlation function and other characteristics of the galaxy distribution argues for initial clouds that were of scale comparable to those of dwarf galaxies. The earliest modern approach to galaxy formation, following the discovery of the CMB, utilized primordial isothermal fluctuations in density whose characteristic mass was identified with that of globular clusters and motivated by the post-decoupling Jeans mass[9]. Primordial adiabatic density fluctuations characterized by the radiative damping mass[1]0 led to a top-down galaxy formation model[11] that predicted excessive CMB anisotropies[12]. This model was revived with the advent of hot dark matter but has not resulted in a satisfactory model for large-scale structure. An early phase transition generally produces isocurvature rather than isothermal fluctuations, and the studied examples of such models result in fluctuation spectra with the largest fluctuations on the smallest scales, leading to a bottom-up evolutionary sequence. Cosmic strings and textures are examples of topological defects that generate non-gaussian isocurvature fluctuations.

It is unfortunate that given primordial clouds of baryons of mass, say, $10^6 - 10^8 M_\odot$, with no metals and, presumably, no magnetic fields, theory cannot distinguish between the following possibilities: fragmentation into substellar fragments, into stars of conventional mass, or into supermassive black holes. Hence, I will develop a phenomenological argument that is suggestive, if not overwhelming. It involves the Principle of Least Extrapolation. I require that BDM candidates should be known to exist and to constitute a significant fraction of the luminous regions of galaxies. The leading candidate, which is the greatest contributor in luminous regions, is the white dwarf. Other possibilities are neutron stars and black holes at the massive end of the primordial initial mass function (IMF), and degenerate dwarfs at the low mass end. One can immediately eliminate planets ($\lesssim 10^{-3}$ of luminous mass), supermassive black holes, and diffuse gas as BDM contenders.

The initial stellar mass function is only studied over a wide dynamical range in the solar vicinity. It represents all stars ever formed. It approximates a power-law with varying slope over the range 0.3 to 100 $M_{\odot}$, peaking at about $0.2M_{\odot}$ and declining towards the hydrogen-burning limit, $0.08M_{\odot}$. No brown dwarfs, defined to be objects below $0.08M_{\odot}$ but greater than the maximum mass of a planet of solar composition, about $0.002M_{\odot}$, have hitherto been definitively detected. The distinction between planet and brown dwarf is based on the partial lifting of degeneracy pressure in the core, resulting in a maximum planetary radius at about 2 Jupiter masses. Some energy release occurs for more massive degenerate dwarfs via slow gravitational contraction (hence *brown*[13]). An alternative measure of the minimum mass of a brown dwarf of primordial composition comes from considerations of opacity-limited gravitational fragmentation of a collapsing cloud. This leads to mass estimates of order $0.001M_{\odot}$, although the calculations assume spherical symmetry and are probably too idealized to be an adequate guide. Of course, above $\sim 1M_{\odot}$, one only measures the current epoch mass distribution, and a past star formation rate must be assumed in order to derive the IMF.

For BDM to consist of compact objects, either brown dwarfs or stellar remnants, the primordial IMF must differ drastically from the present IMF. One could not have formed many solar mass stars. Either the primordial IMF was predominantly brown dwarf-dominated, or else it was top-heavy, with strong suppression of star formation below $\sim 2-3M_{\odot}$. Theory has little to offer in the way of predicting the primordial IMF, but there are several suggestive phenomenological constraints that are described in the following section.

4. PRIMORDIAL IMF

4.1 Star formation theory

Theory is incapable of even estimating the characteristic stellar mass in primordial clouds. In the likely (but not inevitable) event that fragmentation occurred, the available analyses utilize linear perturbation theory to infer a minimum Jeans mass in an idealized collapse geometry. H_2 cooling in primordial clouds results in minimum fragment masses of $\sim 0.01M_{\odot}$. However, it has been argued that spherical collapse does not lead to formation of long–lived fragments, but that anisotropic collapse is the more generic initial condition that will lead to formation of a transient sheet. Such a sheet is unstable to fragmentation. Unfortunately, the non-linear evolution of the fragments is poorly understood. Numerical simulations suggest that a complex filamentary and clumpy structure develops[14]. The role of processes such as accretion and coalescence is unclear. The situation is murkier still if magnetic fields play a dynamical role as in conventional star formation where angular momentum transfer is regulated by coupling to magnetic fields. Angular momentum transfer in primordial clouds is likely to be controlled by disk instabilities. Moreover, it is entirely possible that bipolar outflows, prevalent in nearby star forming regions, develop around forming primordial protostars and provide a feedback mechanism that limits the growth of stellar masses.

4.2 Phenomenology: there were primordial stars

The existence of solar mass stars with metallicities $[Fe/H] < -4$ is a strong indication that ordinary stars formed in an essentially pristine environment. It takes very little in the way of element synthesis and ejection by massive stars, with their short evolutionary time-scale, to pollute to this level. Stars of primordial abundance produce a small amount of CNO by pp-cycle nucleosynthesis, so that stellar evolution with initial $[Fe/H] \lesssim -6$ is generally indistinguishable from zero initial [Fe/H]. However if $[Fe/H] < -4$, there is too little CNO for helium flashes, so that dredge-up is suppressed and yields are reduced for intermediate mass stars.

The study of heavy element abundance patterns in metal-poor stars, in statistical samples with $[Fe/H] < -3$, and in individual more extreme metal-poor examples, reveals the characteristic signatures of both r and s process abundance ratios. This indicates the presence of stellar precursors in the mass range $10 - 50M_\odot$ that are known to be the sites of these elements. Such stars must have existed very early in the proto-galaxy phase, *before* the most metal-poor observed stars had formed. These latter stars are of course the oldest stars in the galaxy and have masses of about $1M_\odot$.

Hence the protogalaxy must have contained stars that spanned essentially the same mass range as conventional stars. This does not of course allow us to infer anything about the mass fraction in such stars, the nucleosynthesis argument and direct observation only requiring a small fraction by mass, of order $Z/Z\odot$, in extreme metal-poor stars.

4.3 The primordial i.m.f. (probably) was different

Several phenomenological arguments attest to a primordial i.m.f. that differed from the solar neighborhood i.m.f. None of these are compelling, but there does seem to be a suggestive trend.

4.3.1 Alpha nuclei

The low dispersion in $\alpha-$nuclei abundances relative to Fe/H reported at this meeting for old disk stars, together with the radial gradient of declining α/Fe as a function of increasing mass and orbital radius, suggests that a change in the IMF has occurred between the epoch of disk formation and today. Of course, one may more directly infer a change in nucleosynthetic yield (heavy element fraction produced relative to net gas mass forming stars), and modification of the IMF is not a unique solution. The coupling of $\alpha-$nuclei, produced by massive stars, to iron abundance, produced in supernovae of type II, suggests that type II supernovae dominated Fe production in the inner galaxy and old disk. This could require a more top-heavy IMF than is presently observed. Alternatively, mass loss might have been less efficient at low metallicity, allowing intermediate mass stars to become supernovae. Such stars are sufficiently short-lived that their nucleosynthetic ejecta would be well coupled to the debris of massive stars. This provides a counter-example of how variable yield, rather than IMF, might be responsible for the observed effect. The enhancement of $\alpha-$nuclei, observed at $[Fe/H] \lesssim -1$ is usually attributed to the shorter evolutionary timescales of $\alpha-$producing stars relative to the SNI usually identified with Fe-producers. However the correlation of α with Fe, as demonstrated by the low dispersion, favors an interpretation via one of the mechanisms suggested above.

4.3.2 Gas content of spirals

The longevity of the gas reservoir in ordinary spirals requires either a modification of the IMF, enhancing the returned gas fraction via a low mass truncation, or else gas infall. The current star formation rate in a galaxy such as the Milky Way would have depleted the gas supply within a fraction of a Hubble time were the local IMF invariant with time and/or position in the galaxy. Tilting the IMF towards massive stars (a top-heavy IMF) or truncating it in regions of intense star formation below $\sim 2M_\odot$ at early times prolongs the gas supply, to give an effective e-folding time of several Gyr as is required. An alternative solution requires gas infall at a rate of $\sim 1M_\odot \mathrm{yr}^{-1}$ to balance the lock–up rate of gas into low mass stars. The current gas infall rate is unlikely to be in excess of $\sim 0.1M_\odot \mathrm{yr}^{-1}$, as inferred from observations of high velocity clouds and, particularly, diffuse galactic x-ray emission fluxes. At earlier epochs, however, infall may have played a greater role.

4.3.3 Starbursts, tidal interactions and galaxy formation

Modelling of galaxies undergoing intense formation, or starbursts, where the star formation rate per unit mass of gas is enhanced by up to two orders of magnitude relative to that in the Milky Way, suggests that the IMF must be top-heavy or deficient in low mass stars[15]. This enhances the gas return fraction from the local IMF value of $R \sim 0.3$ to ~ 0.9, and increases the star formation rate or efficiency, which is proportional to the net mass of gas consumed or $1 - R$, by an order of magnitude. Moreover, those galaxies undergoing the most extreme starburst activity, as measured by the ratio of $L_{60\mu}/L_B \sim 100$ relative to the Milky Way value of order unity, are almost invariably involved in a merger or close tidal interaction. Compelling theoretical modelling suggests that a merger of gas-rich systems strongly enhances the gas concentration as a consequence of tidally induced gas cloud inelastic interactions[16]. This is very likely to lead to the star formation bursts that are observed provided that the star formation efficiency per unit mass of gas is also enhanced. Gas flows to the central region of the merging system may suffice to enhance the efficiency and allow a star formation burst of long enough duration, or else the starburst may consist of transient episodes: the inference of an altered IMF offers a likely but not unavoidable resolution of the enhanced star formation efficiency.

The analogy with galaxy formation is intriguing for two reasons. Mergers and tidal interactions play an important role in hierarchical theories of structure formation: they are inevitable during the galaxy formation process. The inferred star formation rate in a protogalaxy can be inferred from population synthesis modelling of the observed light distribution and spectrum of a galaxy, and one finds that for an old, spheroid population, the protogalactic star formation rate per unit mass was enhanced by some two orders of magnitude relative to that observed today in galactic disks. The analogy with extreme starbursts is consequently rather suggestive. Indeed, the recent products of galaxy mergers are found to exhibit de Vaucouleurs-type radial light profiles, as do luminous ellipticals[17]. However, one cannot account for formation of most spheroids by mergers without involving a precursor population of gas-rich disks that are not seen today in sufficient number but could plausibly have been prevalent in the past.

4.3.4 Indicators of a bottom-heavy i.m.f.?

There are at least two pieces of evidence that give a weak indication of a primordial IMF enhanced in low mass stars. The absence of evidence for massive OB star formation in galaxy cluster cooling flows at no more than 10 percent of the rate concordant with the apparent rate of gas depletion, typically $\sim 100 M_{\odot} yr^{-1}$ in a rich cluster, under the assumption that the cooling gas forms stars with a solar neighbourhood IMF, has led various authors to deduce the presence of large numbers of very low mass stars ($< 0.1 M_{\odot}$) condensing from the cooling flows. The recent detection of as much as $\sim 10^{12} M_{\odot}$ of cold gas inferred to be in dense clouds in the cores of cooling flow clusters greatly weakens any conclusion about the inevitability of low mass star formation, since an alternative reservoir for the cooling flow gas is inferred[18]. Of course such clouds most likely undergo collisions and form stars, but one would now be reluctant to cite cooling flows as providing firm evidence for predominantly low mass star formation.

Another indication of a bottom-heavy IMF has emerged from studies of the faint end of the luminosity function in several globular clusters. A correlation is claimed between the IMF slope over the range $0.2 - 0.4 M_{\odot}$ and the dynamical age of the cluster[19]. Two clusters with long core relaxation time-scales ($\gtrsim 10^9$ yr) contain a steeper IMF ($dN/dlnm \propto m^{-x}$, $x \approx 3$) than is found for another two clusters with core relaxation times of $\sim 10^8$ yr, for which $x \approx 1$. Incompleteness corrections are large in this stellar mass range. However if future studies confirm this trend, one might be tempted to argue that those globular clusters which by virtue of low dynamical age come closest to sampling the initial IMF from which they formed, might be indicative of the primordial halo IMF. Of course, one would still require an enormous extrapolation towards lower stellar masses to obtain the required halo mass, while having formed the globular clusters themselves, which have low M/L, only from stars of mass $\gtrsim 0.1 M_{\odot}$.

5. PRIMORDIAL STAR FORMATION RATE

5.1 Protogalactic star formation rate: general considerations

Population synthesis modelling of galaxy spheroids, previously alluded to in the analogy with starbursts, implies that the characteristic star formation time is less than 1 Gyr. Globular clusters in the Milky Way halo differ in ages, however, by up to 2-4 Gyr. Moreover, the disk, as measured by the white dwarf luminosity function is only 9 Gyr old, and hence formed $\sim 5(\pm 2)$ Gyr after the oldest globular clusters. Evidently, our metal-poor spheroid, which only constitutes a small fraction of the *luminous* mass of the Galaxy, formed over a more extended time-scale, and hence with a lower specific star formation rate, than did the metal-rich spheroidal populations characteristic of the bulk of the light from luminous ellipticals. Metal-poor dwarf ellipticals also reveal evidence for a range in formation age, as inferred from the presence of carbon stars. The specific star formation rate directly observed in metal-poor spheroids is not dissimilar from that indirectly inferred by population synthesis modelling of disks in luminous spiral galaxies. Typical e-folding time-scales in disks are several Gyr.

There is an intriguing dynamical property of these systems. Luminous ellipticals tend to be slowly rotating, and supported by random stellar motions, whereas disks, low luminosity ellipticals, and spheroids are rotationally supported. Star formation rate and efficiency is evidently important in determining galaxy morphology. A high specific star formation rate means high star formation efficiency. In a merging hierarchy, this results in the formation of dense stellar subsystems that merge as a consequence of dynamical friction. There is considerable angular momentum transfer, and the merged core that forms is not rotationally supported. A low specific star formation rate means inefficient star formation. The resulting collapse is gas-rich and dissipative, with the result that a disk forms as angular momentum tends to be conserved by the contracting gas. Disks are likely to be generic units that form. Disk mergers provide a more violent trigger for a starburst, by virtue of the greatly enhanced tidal torques from the stellar components, that lead to a high specific star formation rate.

5.2 Star formation rates in disks and starbursts

To illustrate the physics that enters the star formation rate, I present a simple model for the rate of star formation in two distinct environments. Consider first a quiescent disk forming stars via non-axisymmetric gravitational instabilities that manifest themselves as spiral density waves and operate on the cold atomic and molecular gas components. The disk plausibly maintains itself in a state of marginal instability, with the Toomre parameter $Q \equiv \kappa\sigma/\pi G\mu$ of order unity. Here κ is epicyclic frequency, σ is gas velocity dispersion (or radial velocity dispersion of stars for a stellar disk), and μ is surface density. The disk forms stars if $Q < 1$, and massive stars evolve on a rapid time-scale ($< 10^7$yr) to heat the gas via winds and supernova explosions. This energy input tends to stabilize the disk, but if $Q > 1$, the gas dissipates and cools effectively in the absence of the OB stars to lower Q. At the edge of the disk, the decline in gas surface density suppresses star formation. These various effects are concisely represented in the following expression for star formation rate:

$$SFR(r) = \varepsilon \, \mu \, \Omega(1 - Q), \tag{1}$$

where ε is a parameter that can be identified with star formation efficiency: the fraction of the mass of a molecular cloud converted into stars. Here $\Omega(r)$ is the rotation rate of the disk: for a flat rotation curve, $\varepsilon \approx 2\Omega$. The Toomre parameter can be written as

$$Q = \mu_{crit}/\mu_{gas}; \quad \mu_{crit} \approx \sqrt{2}\Omega\sigma/(\pi G) \approx 8 M_\odot pc^{-2},$$

the numerical value applying in the solar neighborhood where the observed cold gas surface density is about $13 M_\odot \mathrm{pc}^{-2}$. Equation (1) provides an acceptable model for the radial dependence of the star formation rate observed in nearby disks, and yields the history of star formation and enrichment when appropriate assumptions about the initial mass function and infall are made.

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Next, consider a situation in which the star formation rate is temporarily boosted above the steady rate value implied by (1), as might happen following a satellite merger that results in strong tidal torques being exerted on the interstellar gas clouds. The inelasticity of the ensuing gas cloud encounters generates a strong concentration of gas in the inner few kpc of a typical disk, and we may reasonably expect this to result in a starburst, an episode of enhanced star formation. The following argument suggests a simple estimate of the ensuing star formation rate.

Motivated by the three-component model for the interstellar medium[20], I assume that energy input from expanding supernova remnants self-regulates the interstellar gas via formation of a pervasive hot intercloud medium. The hot medium, when its volume filling factor is appreciable, pressurizes the interstellar clouds, which themselves collapse and form stars as they become destabilized. The condition that the porosity be of order unity suffices to constrain, and effectively determine, the star formation rate:

$$P = (SFR/M_{sn}) \times \nu_{sn},$$

where M_{sn} is the mean mass in stars per supernova and ν_{sn} is the 4-volume of a spherically symmetric supernova remnant. One finds that $M_{sn} \approx 200 M_{\odot}$ for a solar neighborhood IMF, and that $\nu \propto p^{-1.4} n^{-0.1}$, where p is the ambient pressure and n is the mean density of the interstellar medium. The self-regulation requirement $P \sim 1$ immediately leads to

$$SFR \propto p^{-1.4} n^{0.1} \ or \ \dot{M}_* \propto \sigma^{5.7}; \tag{2}$$

here SFR is the star formation rate per unit volume, $\dot{M}_*$ is the total star formation rate, and σ is the escape velocity. Now the rate of star formation cannot exceed the gas accretion rate in spherical free-fall, $\sim \sigma^3 G^{-1}$, from which one may infer from condition (2) that $\sigma \lesssim 50$ km s^{-1}. This suggests that star formation is inefficient in gas-rich dwarfs, by a factor of $\sim (\sigma/50 \text{ km s}^{-1})^{2.7}$ for $\sigma < 50$ km s^{-1}. A wind will be driven when the gas density has dropped low enough that cooling is slow over a dynamical time-scale. Massive galaxies undergo transient bursts of star formation at a rate that cannot exceed (2).

6. PROTOGALACTIC RELICS

6.1 Dim giants

The critical surface density below which star formation is suppressed in a disk suggests that there should be a population of giant disk galaxies, whose surface density is low. Candidates for such objects include galaxies such as Malin 1 and 2, and the damped Lyman alpha absorption clouds detected along the line of sight to high redshift quasars. Hierarchical formation models lead to an interesting prediction for such objects: they should have bright, essentially normal, bulges. At early epochs, the potentially dim giants are indistinguishable from normal galaxies. The late infall occurs at large radius in the former case, and this is what distinguishes the disk of a dim giant from that of a normal spiral. One can understand this distinction as a consequence of peak-background modulation: in a cluster or group environment, the late accretion is considerably enhanced onto a density peak of galactic scale relative to what one finds in the field[21].

6.2 Low surface brightness dwarfs

A huge dark dwarf galaxy population is generic to gaussian fluctuation models such as that of cold dark matter. The mass spectrum of density peaks that have just become non-linear contains approximately equal mass per logarithmic mass interval, so that

$$dN/dm \propto m^{-2},$$

whereas the observed dwarf luminosity function is $dN/dL \propto L^{-\alpha}$, with $1 \leq \alpha \leq 1.5$. These dark dwarfs are not seen in nearby galaxy populations, but may be luminous at

$z \gtrsim 1$. The deep B and K counts require either prolific merging of luminous galaxies[22] or a new population of blue dwarfs[23,24] at $z \gtrsim 1$. The multiple component absorption line systems seen along the lines of light to many quasars also have been interpreted in terms of a transient population of star-forming dwarfs, with some supporting evidence being provided by emission line detections[25].

A successful model which explains the proliferation and transient nature of dwarfs at modest redshift appeals to tidal interactions that occur as galaxy groups form[26]. This is a recent ($z \sim 1$) occurrence, at least in a universe with $\Omega = 1$ and relies on the hypothesis that tidal interactions induce starbursts. The dwarfs fade to invisibility by the present epoch: a typical faint galaxy with $B = 26$ at $z = 1$ fades to $M_B = -15, \mu_B = 26.5$ mag/arc-sec^2 at $z = 0$. Natural biasing is inevitable: uncollapsed regions which include most of the volume of the universe contain gas clouds that have formed few if any stars, and may plausibly be identified with the nearby unclustered population of Lyman alpha forest absorption clouds seen towards quasars. Starburst-induced winds heat the intergalactic medium: the dwarfs are sufficiently numerous that the volume filling fraction of the wind-heated IGM is large by a redshift of 5 in a CDM model. This suggests an alternative explanation of the Gunn-Peterson effect, involving collisional ionization and heating to $\gtrsim 3 \times 10^5$K of the IGM. The predicted luminosity function in groups and clusters is similar to that seen in Virgo and Fornax at low luminosities: $\alpha \approx -1.5$ for low surface brightness gas-poor dwarfs. The much larger number of gas-rich dwarfs in the field could plausibly have a sufficiently large effective cross-section to account for the Lyman alpha forest clouds.

7. PROSPECTS FOR DETECTION

7.1 Black holes and neutron stars

The least innocuous of BDM candidates, massive stars must have formed at sufficiently large redshift to have eluded detection via direct and, especially, via indirect searches. The diffuse background radiation signature is potentially observable, but adequate coverage in the infrared spectral region is only just now becoming available with the DIRBE detector on COBE. It is unlikely, however, that a BDM fraction $\Omega \sim 0.1$ would be detectable with current techniques. A more serious problem is pollution by heavy elements ejected as massive stars evolve and die. This may be avoided by appealing to sufficiently massive primordial stars ($\gtrsim 300 M_\odot$) whose yields are greatly suppressed, and/or by efficiently recycling the ejecta from neutron stars in dense star clusters at high redshift[27]. This latter possibility is feasible because Compton cooling helps quench any winds that might disperse the pollutants at $z \gtrsim 100$ from the dense, globular-cluster-like clouds that are the expected sites of primordial star formation. Some early enrichment is actually required, both in the intracluster medium and in the old disk, and BDM could plausibly provide the source of the pollutants.

7.2 White dwarfs

These are the most common of all BDM candidates. Fine-tuning of the primordial IMF is required if the BDM is almost exclusively white dwarfs, but this is hardly an objection. More seriously, one has to consider the overproduction of helium and astration of deuterium. Primordial white dwarfs are likely to be massive ($\gtrsim 1 M_\odot$), because of the larger characteristic mass and zero metallicity of their precursors. Mass loss in the late stages of stellar evolution, to the extent that it is driven by resonant absorption line scattering of radiation, should be less efficient than for conventional stars. The resulting helium yields are correspondingly uncertain. Of course, if most of the ejecta ($\sim$ 90 percent) end up in the intergalactic medium, the *disk* helium abundance is enhanced by $\triangle Y \lesssim 0.05$, an amount that can barely be tolerated within chemical evolution models and reconciled with primordial nucleosynthesis constraints.

White dwarfs as BDM candidates may still be visible if their age is less than about 15 Gyr, in the form of a low luminosity tail to the local white dwarf luminosity function.

These nearby old halo white dwarfs would also have high space velocities, and one expects to find[28] $\gtrsim 1$ per square degree with proper motion $\gtrsim 1$ arc-sec/yr at $m_I \lesssim 22$. A more speculative possibility is via the expected frequency of close white dwarf binaries, some of which should merge. If one identifies Type I supernovae with merging white dwarfs, one might anticipate a frequency of 1 merger/10 yr in the dark halo, were it to consist exclusively of white dwarfs with similar binary characteristics to disk white dwarfs[29]. While observations exclude such a high rate for conventional supernovae in dark halos, it is entirely possible that merging white dwarfs, especially of the massive, primordial variety, might result in "fizzlers", forming a neutron star but with greatly reduced optical signature because of the presence of a compact dense accretion disk. Disk fragmentation and ensuing fragment ejection provides a recoil mechanism that can produce neutron stars with high velocity. A speculative interpretation[30] of high velocity ($\lesssim$ 1000km/s) pulsars seen up to 1kpc above the plane and with predominantly, but not exclusively, downward motion would be in terms of a halo population of massive white dwarfs, some of which (about 0.1 percent) merge to form neutron stars.

7.3 Brown dwarfs

The cumulative infrared signature of massive (up to $0.1M_\odot$ if primordial) brown dwarfs makes them potentially detectable in nearby dark halos as a diffuse glow. The nearest objects to the sun may also be detectable in a proper motion survey at near-infrared wavelengths. The most promising technique, however, for discovering brown dwarfs, as well as most other BDM candidates that span the mass range $10^{-8}M_\odot - 10M_\odot$, is via a gravitational microlensing survey of the Large Magellanic Cloud[31]. The probability of an event for an individual star is only 10^{-6}, but the starlight is amplified by 50 percent over a timescale $\sim 0.2M_x^{1/2}$yr, where M_x is the mass of the BDM candidate in units of a solar mass. Two experiments underway in 1991/92 will monitor up to 10^7 19th magnitude stars in the LMC every night to search for the achromatic, symmetric, non-repeating signal characteristic of a microlensing event.

8. CONCLUSIONS

Dark matter formation almost certainly preceded galaxy formation. Hence we had best understand dark matter before we can hope to understand how galaxies formed. Halo and galaxy cluster dark matter are inescapable as a dominant constituent of their environment. Dark matter in halos and in galaxy clusters is plausibly baryonic: it formed near baryonic matter concentrations, and is in an amount consistent with and, if H_0 is low, even required by primordial nucleosynthesis constraints. Baryonic dark matter most likely consists of a mixture of brown dwarfs, white dwarfs, neutron stars, and black holes, with a strong emphasis on either low mass objects (brown dwarfs $< 0.1M_\odot$) or compact remnants of massive ($\gtrsim 2M_\odot$) objects relative to the sun. Galaxy formation models, as well as observational evidence, suggests that there should be many dark, or at least low surface brightness, galaxies. These could be dim, gas-rich giants or diffuse gas clouds in the field, or gas-poor dwarfs in clusters.

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DISCUSSION

FABER: Could I ask for a clarification? You gave us a justification for enhanced massive star formation during the early–merging phase of galaxies. However, I am confused about the physical motivation for brown dwarfs. Some of the observational evidence you cited comes from globular clusters, yet I associate them with the early–merging phase. Could you comment on circumstances that might favor an enhanced population of brown dwarfs?

SILK: I can only cite phenomenological evidence that is suggestive, but only weakly, of an enhanced low mass star population. Cluster cooling flows may reproduce physical conditions similar to those in an early phase of galaxy formation, and could be forming stars with a brown dwarf–dominated IMF – in fact, some authors argue this has to be the case. I do not know of any even half–way plausible physical argument that favours enhanced brown dwarf formation in either cooling flows or the early–merging phase of galaxy formation, but this is merely indicative of our lack of understanding of the star formation process itself.

PETERSON: In the lowest–metallicity stars found to date, with [Fe/H] about –4, the ratio of light even Z elements with respect to iron is not significantly different from what it is in stars of less extremely low metallicity. As far as these stars represent the earliest stage of (one solar mass) star formation, they constrain the nucleosynthesis mechanism – pointing towards explosive nucleosynthesis in massive stars whose IMF is not radically different from that responsible for subsequent halo enrichment.

SILK: That is exactly my point: the primordial IMF inferred for the first star contained massive stars with an essentially conventional mass function above, say, $10M_\odot$. However, we can say little about the relative mass fraction in lower mass stars, other than that some existed so the primordial IMF could have been almost completely suppressed below a few solar masses.

RENZINI: You have mentioned the possibility of making CDM in clusters by cooling flows producing Jupiters. There is a constraint here that must be taken into account, and that is the amount of iron in the x-ray gas and locked into stars. With a Scalo IMF, type II SNe fall short by a factor of ~ 5 to produce the iron which is seen and by a factor ~ 50 if Jupiter CDM were to have the same iron content as the present day x-ray gas.

SILK: The iron abundance in intracluster gas may be an indicator of a top–heavy primordial IMF that produced at least some of the cluster dark matter in the form of stellar remnants. For example, if even 10 percent of the cluster dark matter were in this form, the inferred nucleosynthetic yield would account for the observed iron.

McNAMARA: You suggested that low mass stars forming in cluster cooling flows may be the form of the dark matter in clusters of galaxies. I wish to point out that the entire gas budget in x-ray emitting gas in clusters accounts for only $\sim 10 - 30\%$ of the virial mass of clusters. Of that gas, only $\sim 10\%$ at most will cool to form low–mass stars over the Hubble time, so there won't be enough Brown dwarfs to bind the cluster by about two orders of magnitude. However, I would agree that this is maybe a plausible mechanism for forming halos in many CD galaxies.

SILK: In order for cluster dark matter to entirely consist of low mass stars as inferred to form at the present epoch in cooling flows, one has to postulate that a much more rigorous cooling flow involving ~ 90 percent of the present cluster mass occurred when the cluster formed.

DJORGOVSKI: The microlensing search for hypothetical halo brown dwarfs strikes me as a very difficult experiment. First, there are many faint, variable objects on the sky. Second, there is a methodological problem: suppose you actually detect one, a star brightens, fades away, and then, by definition, **never does that again.** Now, repeatability is one of the basic requirements for a scientific experiments. How could you ever demonstrate that it was a microlensing event, and not something else?

SILK One would need a series of gold–plated events (with the expected achromatic and time–symmetric signatures) in different stars that were known from both prior and subsequent observation to be "normal" stars, i.e. stars that did not appear to be variables or have chromospheric activity.