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## NEUTRON STARS AND BLACK HOLES AS MACHOs

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### ABSTRACT

We consider the contribution of neutron stars and black holes to the dynamical mass of galactic halos. In particular, we show that if these compact objects were produced by an early generation of stars with initial metallicity  $\lesssim 10^{-4} Z_{\odot}$ , they can contribute at most 30%–40% of the Galactic halo mass without creating supersolar levels of enrichment. We show that the case for halo neutron stars and black holes cannot be rejected on metal overproduction arguments alone because of the critical factor of the choice of progenitor metallicity in determining the yields. We show that this scenario satisfies observational constraints, similar to but no more severe than those faced by halo white dwarfs. We also discuss the recent results on halo microlensing, the presence of enriched hot gas in clusters and groups of galaxies, and other observations. If there are halo neutron stars and black holes, they will be detected in the future as longer timescale events by microlensing experiments.

*Subject headings:* black hole physics — dark matter — stars: neutron

### 1. INTRODUCTION

Studies of the rotation curves of spiral galaxies and the dynamical behavior of galaxy clusters have shown that most of the matter in our universe is invisible. Although most of the dark matter is believed to be nonbaryonic, a significant component must be baryonic (see, e.g., Copi, Schramm, & Turner 1995). One particular class of baryonic dark matter candidates consists of objects from about planetary masses to several solar masses, collectively called MACHOs. In the last few years, several experiments have used the gravitational microlensing of stars in the Magellanic Clouds and in our Galaxy to constrain the nature and amount of such MACHOs in the Galactic halo.

These experiments have had surprising results. Brown dwarfs, which were natural candidates for subluminescent MACHOs, do not form a significant fraction of the Galactic halo. In fact, MACHOs in the mass range  $10^{-7}$ – $0.02 M_{\odot}$  make up less than 20% of the dark matter of our halo (Renault et al. 1997). Star counts from the Hubble Deep Field (HDF), along with microlensing results, are consistent with negligible halo dark matter contributions from substellar objects such as brown dwarfs (see, e.g., Chabrier & Méra 1997). Furthermore, the MACHO collaboration observed the microlensing of stars in the direction of the Large Magellanic Cloud (LMC) by objects that, based on their 2 yr data of eight microlensing events, have a most probable mass of about  $0.5^{+0.3}_{-0.2} M_{\odot}$  (Alcock et al. 1997). If these objects are in our halo, they could comprise about half of the halo's mass based on a comparison with the optical depth associated with an all-MACHO halo.

Thus there are now at least two Galactic dark matter problems: the nature of halo MACHOs that are detected through microlensing, and the composition of the remainder of the dark halo. The nature of the observed MACHOs is not yet resolved. There are competing interpretations for the microlensing data ranging from nonbaryonic halo objects such as primordial black holes (BHs) to stellar contributions from a Galactic component such as the thick disk or spheroid, or from the warping and flaring of the Galactic disk toward the LMC (Bennett 1998, and references therein). Other models make a case for non-Galactic lenses

such as microlensing by stars in the LMC or Small Magellanic Cloud (SMC) themselves (self-lensing), or an intervening component between the Galaxy and the LMC, such as a dwarf galaxy or a tidal tail from the LMC. At present, no model gives a compelling explanation for all aspects of the MACHO problem.

In this paper, we consider baryonic objects as one possible solution for the MACHO dark matter problem. The most likely experimental MACHO mass at present is about  $0.5 M_{\odot}$ , which is too high for typical brown dwarf masses since hydrogen burning starts at  $\sim 0.08 M_{\odot}$ . A solar mass of 0.5 suggests the presence of white dwarfs (WDs; Adams & Laughlin 1996; Fields, Mathews, & Schramm 1997). Alternative candidates for baryonic MACHOs are neutron stars (NSs) and low-mass black holes (LMBHs).

Models of WD-dominated halos experience several difficulties. WD progenitors (taken to be typically 2–4  $M_{\odot}$  in previous work) produce large amounts of enriched gas, which must be ejected by some mechanism into the intragroup medium since such gas is not seen in the Galaxy today. Since neither WD progenitors nor planetary nebulae have sufficient kinetic energy in their winds to expel the enriched gas, the presence of supernovae (SNs) from the death of massive stars (which produce NSs and BHs) is necessary. In addition, the lack of the signature expected from the early luminous phase of WD progenitors in deep galaxy surveys constrains the WD fraction in galaxy halos today to be less than 10% (Charlot & Silk 1995). Further constraints on a WD component to the Galactic halo come from searches for faint stellar objects in the HDF, down to  $I = 26.3$  (Flynn, Gould, & Bahcall 1996), and from studying the luminosity evolution and cooling history of WDs (Graff, Laughlin, & Freese 1998).

Furthermore, given that roughly half of Population I stars are in binaries, a significant fraction of a WD-dominated halo could plausibly be in binary systems. These would generate, through WD-WD mergers, a larger rate of Type Ia SNs than is observed (Smecker & Wyse 1991). The chemical enrichment in  $^{56}\text{Fe}$  from Type Ia SNs would reach far above solar values since the timescales for Type Ia SNs greatly exceed the initial period of enhanced star formation,

which prevents prompt mixing and dilution of the ejecta on large scales. These SNe also do not leave remnants that could lock up the created heavy elements permanently (Smecker & Wyse 1991).

NSs and BHs from Type II SNe avoid these difficulties. Type II SNe occur over much shorter timescales than do Type Ia, and they leave a significant fraction of their synthesized heavy elements in the NS or BH remnants. In addition, the abundance ratios of the hot X-ray-emitting gas seen in clusters of galaxies (Mushotzky et al. 1996) appear to favor a Type II, rather than Type Ia, SN origin, although this is subject to some debate (see, e.g., Ishimaru & Arimoto 1997). Lastly, theoretical work (Woosley & Timmes 1996) indicates that an early generation of massive stars in the Galaxy could indeed have generated a large number of LMBHs through Type II and Ib SNe explosions.

Models with halo NSs and LMBHs face at least two challenges. The most likely MACHO mass as reported by Alcock et al. (1997) is lower than the typical masses of NSs ( $\sim 1.4 M_{\odot}$ ) and LMBHs ( $1.5$  to several  $M_{\odot}$ ). We address this point in the discussion section, but note here that the first year's data from the Expérience de Recherche d'Objets Sombres (EROS2) experiment (Palanque-Delabrouille et al. 1998) may indicate higher MACHO masses. Second, the massive stars that could create NSs and BHs eject large amounts of enriched material when they become SNe, which may contaminate the interstellar medium with  $^4\text{He}$  and heavy elements beyond solar values.

In this paper, we focus on the latter challenge and show that the case for a halo with significant mass fractions in NSs and BHs is not easily dismissed from arguments based solely on excessive pollution from the ejecta of the SNe creating these objects. This conclusion is contrary to previous work (see, e.g., Ryu, Olive, & Silk 1990), primarily because we use recent results from Woosley & Weaver (1995, hereafter WW95) for the nucleosynthetic yields from the evolution of massive stars of low metallicity that explode as Type II SNe. These stars do not have the prohibitively high metal yields that are associated with solar metallicity progenitors. Our goal here is to show that this, therefore, is not *prima facie* evidence to reject halo NSs and BHs and to place an upper limit on their contribution given the greatest viable stretch of parameters. Although this scenario is not free of assumptions (§ 2), we show that this upper limit is consistent with other related constraints.

In order to maximize the contribution of NSs and LMBHs to the halo dark matter, we focus on an initial burst involving only high-mass stars and calculate the yields from just this epoch. This early generation of massive stars create a large population of compact objects in the initial phase of the formation and evolution of the Galaxy. The generated remnants are mostly NSs and LMBHs, with some heavier BHs. The fraction of NSs relative to BHs depends on the maximum mass of NSs; LMBHs could have masses as low as  $1.5 M_{\odot}$  (Brown & Bethe 1994).

The plan of this paper is as follows: in § 2, we discuss in detail the assumptions that we make for a scenario that creates halo NSs and BHs. In § 3, we compute the yields in hydrogen,  $^4\text{He}$ , and metals generated by the SNe from this early population. We derive a maximum mass fraction in the halo made of remnants from these stars for three cases of initial metallicity of the progenitor. We then calculate the mass of gas required initially for the Local Group (LG) to dilute the final abundances of  $^4\text{He}$  or metals in the leftover

gas to solar values. In § 4, we discuss some implications of this scenario, relevant constraints, and some recent observations. We then conclude in § 5.

## 2. A POSSIBLE NEUTRON STAR/BLACK HOLE SCENARIO

A halo with a significant fraction of its mass in stellar remnants must meet certain constraints of mass and metallicity. The stars that create NSs and BHs also leave behind ejecta with enrichment that is above solar values and mass that exceeds that in the remnants and, therefore, those of the present Galactic disk and bulge. A scenario that proposes NSs and BHs as significant contributors to halo dark matter must necessarily invoke at least the following assumptions. A starburst that selectively forms only massive stars, and in which most of the baryons participate, is required. Furthermore, this burst must occur sufficiently early in the history of the universe, as such a bright phase is not seen at lower redshifts. The prompt recycling of stellar debris that occurs in standard chemical evolution is not desirable for an NS/BH scenario, since stars in present galaxies show a large spread in metallicities and presumably reflect enrichment from generations subsequent to any proposed early starburst. Therefore, some mechanism is needed that removes the initially metal-rich ejecta and that could aid any dilution that ensues, such as winds or outflows from the star-forming regions. We discuss these chosen assumptions below; we will see in § 3 that low- $Z$  stars alleviate any dilution constraint compared with high- $Z$  stars.

We assume a dynamical mass of  $10^{12} M_{\odot}$  for a halo of radius 100 kpc (see, e.g., Peebles 1995, plus the assumption that  $\rho_{\text{halo}} \sim r^{-2}$ ). Microlensing experiments constrain the optical depth along the line of sight in MACHOs from a lensing event, which gives a direct estimate of the total mass in MACHOs. To extend this to a halo baryonic fraction, we need to divide this by the total mass of the halo, which is uncertain and dependent on specific models and assumptions. In the results of the MACHO experiment, according to Alcock et al. (1997) and K. Griest (1997, private communication), the halo mass fraction of MACHOs can take values between 10% and 100% for different halo models, excluding experimental error; however, the most likely total mass in halo MACHOs within 50 kpc has been very stable at about  $2 \times 10^{11} M_{\odot}$ . Keeping these considerations in mind, we first derive the maximum masses in halo MACHOs in NSs and LMBHs, which we can extend to their halo mass fraction.

In this work, we concentrate on the LG when deriving limits from specific constraints. We assume that the two most luminous, dominant spiral galaxies in the LG, the Milky Way, and M31 each processed  $\sim 10^{12} M_{\odot}$  of primordial gas through an early generation of massive stars. This first generation was made of very low metallicity ( $\ll Z_{\odot}$ ) gas, which cools inefficiently and could favor the formation of higher stellar masses (Adams & Laughlin 1997). Furthermore, the maximum stellar mass that is stable increases with decreasing metallicity. One can approximate this maximum mass as (Adams & Laughlin 1997)  $M_{*,\text{max}} \approx 114 M_{\odot} (1-2.4Z)^2$ , which is approximately  $114 M_{\odot}$  for very small  $Z$ . From these arguments, we take a range of progenitor masses 10–100  $M_{\odot}$ , which create NSs and BHs through Type II SNe. We consider only stars with masses above 10  $M_{\odot}$  to maximize the number of NSs and LMBHs, and we assume a Salpeter initial mass function (IMF) where the number of stars born per unit mass interval  $\xi(M) \propto M^{-2.35}$ .

Although the present-day disk IMF is biased toward low-mass stars, there is evidence for significant high-mass star activity in the past. One possible explanation is a bimodal star formation history, involving early IMFs skewed toward high-mass stars (Elbaz, Arnaud, & Vangioni-Flam 1995; Fields et al. 1997). Elbaz et al. (1995) point out that observations of starburst galaxies, in which the star formation activity and the relative number of massive stars appear related, suggest a truncated IMF.

As we show in this work, the composition of the progenitor star strongly determines that of its ejecta, particularly the ejecta's metal content. The lower the metallicity of a star, the weaker its pollution of the surrounding gas when it becomes an SN, and the higher the mass of the remnant. Thus a  $Z = 0$  star is the most favorable for creating galactic halos with a significant fraction in NS/BH remnants. However, self-enrichment of star-forming regions eventually leads to stars of higher metallicities. This problem is less serious if the timescale for the early massive star formation is short compared to the mixing timescale for the star-forming regions. We will therefore assume a burst approximation; i.e., there is no immediate recycling of stellar ejecta as in standard chemical evolution. The redshift at which such a burst occurred can be constrained by background light limits measured today; this is derived in § 4.

The star formation characteristic of the present epoch, where the rates of SNs are much lower and whose ejecta are mostly incorporated into new generations of stars, begins later in the history of the universe. The Galactic disk and halo stars are not formed in our treatment explicitly; we assume that the baryons that form such Population I and II stars are not enriched by the earlier starburst, or Population III, phase. Such a segregation could occur if galactic winds accompanying the burst phase removed associated polluted ejecta, leaving a fraction of material behind which eventually goes into Population I and II stars. As Population II stars have a mean metallicity of about  $1/30 Z_{\odot}$ , this segregation of the material forming baryonic MACHOs from that forming disk and halo stars must be efficient, and it is essential to the scenario discussed here.

In contrast to the case of Population I and II stars, the hot X-ray gas that is seen in many clusters and groups of galaxies contains a significant fraction, if not most, of the baryons in these systems and is enriched in metals to about  $Z_X \sim 0.3 Z_{\odot}$ , with some cases approaching solar values (see, e.g., Mulchaey et al. 1996; Mushotzky et al. 1996). In this work, we will use this general constraint from studies of this X-ray gas, rather than the range of observed abundances in Population I and II stars, since we are interested in the remnants from a stellar phase that involved the bulk of the baryons. We take the degree of enrichment in intracluster and intragroup gas in other systems to be roughly solar in metals. As the enriched X-ray gas exists in systems that also have galaxies containing low- $Z$  stars, a fair fraction of the baryons in such systems may well have undergone stellar processing separately from the present stars of the galaxies, similar to what we have postulated here. We discuss in § 4 how the self-enrichment of disks can be distinct from any early starburst phase. Note further that the combined baryonic mass in the Galactic disk and halo stars is at most a few percent of the total baryons associated with the Galaxy in its burst phase and will not alter the main conclusions of this paper.

In the next section we use the results of WW95 for the

integrated yield from the early generations of massive stars. We assume that the SNs associated with this early stellar phase can effectively drive winds. Two outcomes are possible: (1) the winds could remove the metal-rich ejecta from the protogalactic regions and then from the LG itself, or (2) they could mix the polluted ejecta with the ambient primordial gas outside early star-forming regions. The second option has the potential to constrain the mass of baryons that participate in an early burst and the final mass in remnants, given a dilution criterion. We do this for the LG in § 3, where we derive the baryonic mass required to form the LG in order to avoid supersolar  ${}^4\text{He}$  or metal values in the diluted gas remaining after the first epoch of stellar processing. This provides a reasonable upper limit to the contribution of halo NSs and BHs in the extreme case of retaining all of the enriched ejecta, i.e., no mass loss. We choose solar values as an average final LG metallicity for the reasons discussed above; although  ${}^4\text{He}$  abundances are not measured in the X-ray gas, we include this case, since we will see that  ${}^4\text{He}$  is more constraining than metals as far as dilution requirements are concerned for the ejecta of low- $Z$  massive stars. Note that if mass loss from the LG does occur and the enriched undiluted gas is ejected through galactic winds and outflows, abundances in the leftover gas can more easily remain at subsolar values. We do not consider this explicitly in this work, since this would necessitate further assumptions on the nature, mass, and metallicity of the intergalactic medium.

Finally, we consider the *total* mass in NSs and BHs. The actual fraction of NSs versus BHs depends on the uncertain maximum mass of NSs. Some authors have recently argued that stars of masses in the range  $18\text{--}30 M_{\odot}$  could leave remnant LMBHs after exploding as Type II SNs (Brown & Bethe 1994; Woosley & Timmes 1996). LMBHs may be formed when the mass of a remnant compact object exceeds  $1.5 M_{\odot}$  (Brown & Bethe 1994). Also, observations may indicate an upper limit to the NS mass of  $1.5 M_{\odot}$  (Brown, Weingartner, & Wijers 1996). Finally, simulations of Type II SNs (WW95; Timmes, Woosley, & Weaver 1996) of low-metallicity stars ( $Z \leq 10^{-4} Z_{\odot}$ ) with masses above  $\sim 15 M_{\odot}$  show that their remnants have masses that exceed  $1.5 M_{\odot}$ . We therefore derive a minimum mass fraction in NSs by assuming that the smallest progenitor mass for an LMBH is about  $15 M_{\odot}$ . If NSs can have masses above  $\sim 1.5\text{--}2 M_{\odot}$ , the halo remnants in our results would have fewer BHs.

### 3. RESULTS

In this section, we calculate the IMF-integrated yields for a burst involving only massive stars of very low  $Z$ , as described in § 2, and for  $Z = Z_{\odot}$  stars for comparison. We show that the enrichment increases with the progenitor's metallicity, with  $Z = Z_{\odot}$  stars resulting in the familiar extreme metal pollution, and  $Z = 0$  stars having the least enriched ejecta and the highest mass left in remnants. We then derive the baryonic requirement for the LG, given the scenario described in § 2, for dilution of the ejecta from such an early phase to solar values in  ${}^4\text{He}$  or metals. Interestingly, the dilution requirement for  ${}^4\text{He}$  is more stringent than that for metals.

We use WW95 to calculate the yields for the range of high-mass stars ( $10 \leq M/M_{\odot} \leq 100$ ) of metallicities  $Z = 0$  (case 1), and  $Z = 10^{-4} Z_{\odot}$  (case 2). We then fit the values for the ejected masses in hydrogen,  ${}^4\text{He}$ , and metals, as well

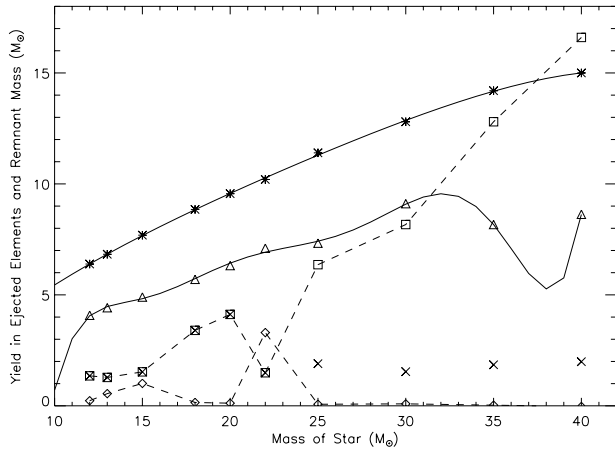


FIG. 1.— $Z = 0$  stars from WW95: ejected masses in hydrogen (asterisks),  ${}^4\text{He}$  (triangles), and metals (diamonds). Also shown are the masses in post-SN remnants for the minimal and maximal ejecta models (squares and crosses, respectively) from WW95; dashed lines are drawn through to guide the eye for the diamonds and squares. Solid lines, where drawn, represent the polynomial fit for that case. All quantities are in solar mass units.

as remnant masses, as a function of the mass of the star in the range  $10\text{--}40 M_{\odot}$ . We expect minimal mass loss effects during the main-sequence lifetimes of the low-metallicity progenitor stars, but there are significant uncertainties in the energy, location, and specific type of mechanism in launching the shock that leads to SNs in stars more massive than  $40 M_{\odot}$ . The remnants in these cases are most likely higher mass BHs (WW95). The role of fallback and late-time accretion makes estimating the final remnant mass and the element yield less reliable. Here we extend the mass fractions in the four quantities of interest from their values at  $40 M_{\odot}$  to the range  $40\text{--}60 M_{\odot}$ . Above  $60 M_{\odot}$ , we assume that the entire star collapses into the remnant.

In Figures 1 and 2, we show the yields of hydrogen,  ${}^4\text{He}$ , metals, and remnant masses for stars of masses  $10\text{--}40 M_{\odot}$  in cases 1 and 2, respectively, with various symbols and the solid lines representing the values from WW95 and a polynomial fit. Figure 1 shows a polynomial fit for the hydrogen and  ${}^4\text{He}$  yields only. For progenitor masses above 25 or  $30 M_{\odot}$ , a star in the tables of WW95 had more than one case of the final kinetic energy of the ejecta at infinity, with models A, B, and C having progressively larger SN shock energies. We chose the model for which this value was closest to  $1.2 \times 10^{51}$  ergs, i.e., model A in WW95, which had the lowest total ejected masses compared to models B or C. Clearly, the model with minimal ejecta will produce rem-

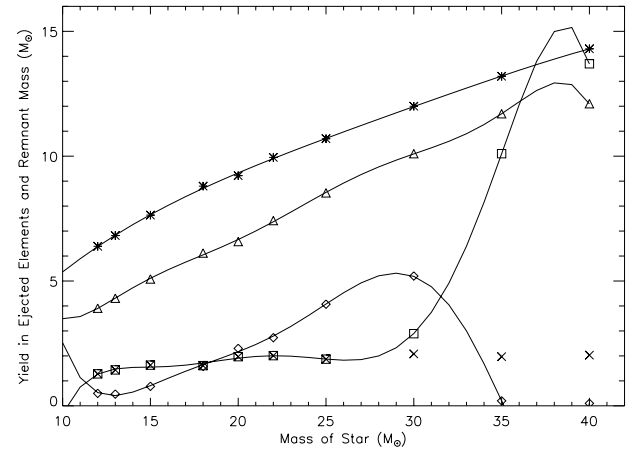


FIG. 2.— $Z = 10^{-4} Z_{\odot}$  stars from WW95: ejected masses in hydrogen (asterisks),  ${}^4\text{He}$  (triangles), and metals (diamonds). Also shown are the masses in post-SN remnants for the minimal and maximal ejecta models (squares and crosses, respectively) from WW95. Solid lines represent the polynomial fit for each case. All quantities are in solar mass units.

nants with larger masses than one with maximal ejecta. Figures 1 and 2 show the remnant masses for the models with maximal ejecta to illustrate the point that depending on the explosion energy, solar-mass compact objects can result from stars as massive as  $40 M_{\odot}$ .

From the figures we see that there is generally more variability in the yields of zero-metallicity stars (except for hydrogen) due to their poorly understood structure and evolution. We obtained good fits only for the hydrogen and  ${}^4\text{He}$  yields in case 1, and we show the ejected mass and remnant masses in Figure 1 to emphasize their fluctuations. To compute metal yields in case 1 integrated over the whole IMF, we took average values for mass bins of  $5 M_{\odot}$  over  $10\text{--}40 M_{\odot}$ , including separately the peak at  $22 M_{\odot}$ ; the mass left in remnants for case 1 was taken to be the difference between  $10^{12} M_{\odot}$  and the integrated post-SN output in hydrogen,  ${}^4\text{He}$ , and metals. Above this mass range, we followed the procedure described earlier.

The  $Z = 0$  stars have lower integrated yields in heavy elements and can create galactic halos with higher mass fractions in NSs and BHs. Table 1 shows the computed elemental yields and remnant masses in solar mass units for cases 1 and 2 resulting from a stellar population of total mass  $10^{12} M_{\odot}$ . This is the mass processed initially by each galaxy in the Group into massive stars. Also shown are the mass fractions of  ${}^4\text{He}$  and metals ( $Y$  and  $Z$ ) in the ejected gas relative to solar values and the fraction of the total halo

TABLE 1  
COMPUTED ELEMENTAL YIELDS AND REMNANT MASSES

Case	$Z_{\text{star}}$	$M_H$ ( $M_{\odot}$ )	$M_{{}^4\text{He}}$ ( $M_{\odot}$ )	$M_Z$ ( $M_{\odot}$ )	$M_{\text{rem}}$ ( $M_{\odot}$ )	$f$	$Y_{\text{gas}}/Y_{\odot}$	$Z_{\text{gas}}/Z_{\odot}$
1.....	0	$3.9 \times 10^{11}$	$2.35 \times 10^{11}$	$1.59 \times 10^{10}$	$3.6 \times 10^{11}$	36%	1.33	1.31
2.....	$10^{-4} Z_{\odot}$	$3.78 \times 10^{11}$	$2.77 \times 10^{11}$	$6.32 \times 10^{10}$	$2.89 \times 10^{11}$	29%	1.40	4.65
3.....	$Z_{\odot}$ (mE)	$3.35 \times 10^{11}$	$2.86 \times 10^{11}$	$9.76 \times 10^{10}$	$2.81 \times 10^{11}$	28%	1.45	7.18
	$Z_{\odot}$ (ME)	$3.35 \times 10^{11}$	$2.86 \times 10^{11}$	$1.43 \times 10^{11}$	$2.36 \times 10^{11}$	24%	1.36	9.92

NOTE.—For three cases of initial metallicity of the progenitor star, the yields are shown in hydrogen,  ${}^4\text{He}$  and metals, and remnant masses in solar mass units from a stellar population of mass  $10^{12} M_{\odot}$  per galaxy. Also shown are the mass fractions of the ejected gas in  ${}^4\text{He}$  and metals relative to solar values and the final halo mass fraction  $f$  in remnants for a galactic halo of total mass  $10^{12} M_{\odot}$ .

mass in remnants,  $f \equiv M_{\text{rem}}/10^{12} M_{\odot}$ .  $f$  should be viewed as an upper limit, since the stellar remnants that are created here are assumed to eventually reside in the galactic halos that form later. For comparison, we include the case of solar metallicity progenitors (case 3) for both the minimal ejecta (mE) and maximal ejecta (ME) models from WW95. We assume  $Z_{\odot} = 1.89 \times 10^{-2}$  and  $Y_{\odot} = 0.275$  by mass fractions.

From these results we see that there is more total mass in remnants and ejected gas that is less metal-rich for  $Z = 0$  stars as compared to the  $Z = 10^{-4} Z_{\odot}$  stars. For all cases the minimum fraction of these remnants in NSs is 24% from stars of mass 10–15  $M_{\odot}$ . Although each set of progenitors shown in Table 1 has very different metal enrichment in the ejecta,  $Y/Y_{\odot}$  is roughly the same for all of them.

If we require that the Galaxy and M31 have, on average, solar abundances or lower in  $^4\text{He}$  and metals, we need to dilute the enriched ejecta from each galaxy (Table 1) with a reservoir of unprocessed gas (at the same metallicity as the progenitors for cases 1 and 2). This is done in Table 2 for two values of the primordial  $^4\text{He}$  abundance: 0.232 (Copi et al. 1995) and the high value of 0.249 (Tytler, Fan, & Burles 1996). The initial mass of gas needed for dilution (including the  $2 \times 10^{12} M_{\odot}$  for the stellar processing in M31 and the Galaxy) will depend on whether we have the final  $Y_{\text{gas}}$  or  $Z_{\text{gas}}$  approach solar values. Table 2 shows the baryonic requirement for the entire LG for either purpose for cases 1 and 2, and the final enrichment in both quantities relative to solar values. The overall range of initial gas masses from which the LG formed is  $2.4\text{--}8.1 \times 10^{12} M_{\odot}$ .

An alternative for lowering final abundances is to invoke the loss of most of the metal-rich ejecta from the Group with time, as is done for some WD models (see, e.g., Fields et al. 1997). But we see that even without the loss of metal-rich gas, a significant Galactic halo fraction in NSs and BHs can be attained if, on average, the gas in the Group has solar metallicity. Table 2 also shows that, except for one listed case, the requirement that  $^4\text{He}$  in the leftover gas be, at most, solar guarantees metallicities below solar. In other words,  $^4\text{He}$  is *more* constraining than metals as far as dilution requirements are concerned for the ejecta of massive stars.

Table 2 illustrates the extreme metal enrichment from massive stars of solar metallicity and how unfavorable such stars are for creating a large population of compact objects. For example, to dilute the metal-rich ejecta from case 3 stars to solar  $Z$  values, the LG must form from primordial

gas of initial mass  $\gtrsim 10^{13} M_{\odot}$ . This is prohibitively large compared with the corresponding  $2.4 \times 10^{12} M_{\odot}$  for case 1.

Within the uncertainties in stellar structure and evolution, the case for a halo with significant mass fractions in NSs and BHs is not easily dismissed from arguments based solely on excessive contamination of the intragroup medium with heavy elements. Such arguments pose serious difficulties for higher metallicity progenitor stars such as the  $Z = Z_{\odot}$  case. In contrast, NSs and BHs produced by very low metallicity massive stars can exist in the Galactic halo without overproducing metals or  $^4\text{He}$ . There are, however, several other issues that relate to the consequences of the formation of such halos; we proceed to address them next.

#### 4. DISCUSSION

We have derived halo mass fractions in NSs and BHs for the scenario described in § 2, and the baryonic requirement for dilution of the ejecta to solar abundances for two cases of very metal-poor stars. As this population of compact objects is created astrophysically, this scenario is subject to several observational constraints, which include big bang nucleosynthesis limits on the baryon density and background light limits. Also of relevance are measurements of the mass and metallicity of gas presently in the Galaxy, the LG, and other systems, and the role played by subsequent stars in enriching the Galaxy.

First, as shown in the previous section, for the ejecta from stars that formed M31 and the Galaxy to not overenrich the ambient gas with respect to solar abundances, we need a large amount of primordial gas that was not processed through stars that could dilute the enriched ejecta. For both  $Z = 10^{-4} Z_{\odot}$  and  $Z = 0$  stars, that translated into an initial baryonic reservoir of  $\sim 2\text{--}8 \times 10^{12} M_{\odot}$ . Big bang nucleosynthesis constrains the cosmological density of baryons  $\Omega_b \equiv \rho_b/\rho_c$  to lie in the range  $0.01 \leq \Omega_b h^2 \leq 0.024$ , where  $h \equiv H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (Copi et al. 1995). Here  $\rho_c$  is the critical density required to close the universe,  $\rho_c = 2 h^2 10^{-29} \text{ g cm}^{-3} \simeq 3 h^2 \times 10^{11} M_{\odot} \text{ Mpc}^{-3}$ ; for a range of 0.4–1.0 for  $h$ ,  $\Omega_b$  can vary from 1% to 15%. Recent measurements of the primordial deuterium abundance in high-redshift quasar absorption systems have yielded  $\Omega_b \simeq 0.02 h^{-2}$  (Burles & Tytler 1998), which gives a density in baryons of  $\rho_b \simeq 6 \times 10^9 M_{\odot} \text{ Mpc}^{-3}$ .

Given  $\rho_b$ , and that the LG is required to have assembled from the range of initial baryonic masses in Table 2, we see that a baryon-gathering radius of  $\sim 10 \text{ Mpc}$  is necessary. This volume contains a baryonic mass of about  $3 \times 10^{13} M_{\odot}$ , while the dynamical (i.e., total) masses of all of the groups of galaxies present in this volume, including the LG, is estimated at about  $8 \times 10^{13} M_{\odot}$  (Tully 1987). We assume that there is no relative baryon concentration in the LG; i.e., the LG will receive some fraction of the baryons in the 10 Mpc radius volume, depending on the estimates for the total mass of the LG. Such a partitioning will not be in conflict with the existence of field galaxies or groups around us, and it can then be compared to the requirements for dilution from Table 2.

One measurement of the dynamical mass of the LG, based on the least action principle, gives  $M_{\text{LG}} \sim 6 \times 10^{12} M_{\odot}$  (see, e.g., Peebles 1993). This is 8% of the dynamical mass in galaxies in the volume of radius 10 Mpc and gives the LG about  $2 \times 10^{12} M_{\odot}$  in baryons, which is close to the lowest mass in Table 2. In this case, only the  $Z = 0$  progeni-

TABLE 2

BARYONIC REQUIREMENT FOR ENTIRE LOCAL GROUP

$Z_{\text{star}}$	$Y_{\text{gas},i}$	$M_{\text{gas},i}/M_{\odot}$	$Y_{\text{gas},f}/Y_{\odot}$	$Z_{\text{gas},f}/Z_{\odot}$
0 .....	0.232	$4.7 \times 10^{12}$	1	0.42
	0.232	$2.4 \times 10^{12}$	1.22	1
	0.249	$6.5 \times 10^{12}$	1	0.29
	0.249	$2.4 \times 10^{12}$	1.23	1
$10^{-4} Z_{\odot}$ .....	0.232	$5.7 \times 10^{12}$	1	1.3
	0.232	$7.2 \times 10^{12}$	0.96	1
	0.249	$8.1 \times 10^{12}$	1	0.89
	0.249	$7.2 \times 10^{12}$	1.01	1

NOTE.—For two cases of initial metallicity of the progenitor star and two primordial  $^4\text{He}$  values, the mass of initial gas required to dilute either  $Y$  or  $Z$  of the enriched ejecta from both M31 and the Galaxy to solar values, with the resulting final values in both  $Y$  and  $Z$  of the gas, are shown relative to solar values.

tors that have  $Z_{\text{gas},f} = Z_{\odot}$  are permitted, and even then just barely. In another analysis involving the least action principle, Dunn & Laflamme (1993) find that  $M_{\text{LG}} \sim 2.2 \times 10^{13} M_{\odot}$ . For this mass, the LG has 28% of the dynamical mass in the galaxies in a volume of radius 10 Mpc, and thus receives just over  $8 \times 10^{12} M_{\odot}$  in baryons. This number is approximately equal to the highest mass in Table 2, and roughly all of the cases in Table 2 are permitted. Therefore, if we require the LG to have assembled from the range of initial baryonic masses in Table 2, at least two cases are not in conflict with the existence of field galaxies or groups in a volume of radius up to 10 Mpc.

There may be a large amount of unprocessed gas (mostly hydrogen) and/or processed gas from early phases of star formation in the intragroup medium today. Depending on how much primordial gas mixed with the ejecta of early stars or became locked in later stellar generations, the present gas content of the LG could be about a few times  $10^{11}$ – $10^{12} M_{\odot}$  (Table 2). Gas remaining from forming the Group may not have been completely retained if the gravitational potential of the LG is insufficient. If this gas is still present, it must be cooler than current experimental limits on soft X-ray background detections. Unfortunately, the total mass of hydrogen in the LG is not very well known. From 21 cm observations, the Galaxy is constrained to have about  $5 \times 10^9 M_{\odot}$  in neutral hydrogen (Henderson, Jackson, & Kerr 1982). However, recent observations of high-velocity clouds that contain neutral hydrogen indicate that these clouds alone, assuming that they are gravitationally bound, may have a total mass of  $\sim 10^{10}$ – $10^{11} M_{\odot}$ , depending on the amount of dark matter that exists in the Galaxy (L. Blitz 1997, private communication). The fraction of the intragroup medium represented in the high velocity clouds is more uncertain, but it is possible that these clouds are all that is left today of the initial gaseous reservoir that formed the LG.

In this work, we assume that an early phase of star formation is widespread, with efficient mixing occurring outside the star-forming regions ensured by the effects of heating and winds from SNs. Observations of present starburst galaxies do show that they can drive large-scale winds that do not necessarily diminish the ongoing massive star formation (Heckman, Armus, & Miley 1987). Therefore, for the LG we expect any leftover gas, if it has remained trapped in the Group potential, to be distributed in the intragroup medium and to have cooled to  $10^5$ – $10^6$  K. The upper limit is set by constraints from diffuse soft X-ray emission and the lower limit by the absorption features expected from any large amount of neutral hydrogen in the LG, which are not seen. In this temperature range the intragroup medium is least constrained at  $10^6$  K by specific emission features such as O VI, as compared to  $\sim 10^5$  K, where the hydrogen column density is limited to  $\sim 10^{17} \text{ cm}^{-2}$ , or a mass of less than  $10^9 M_{\odot}$  over an area of 1 Mpc<sup>2</sup> for the LG. The presence of large amounts of intragroup gas at temperatures of about  $10^6$  K and with  $Z \gtrsim 0.3 Z_{\odot}$  is therefore an important target for future observations.

We now consider contributions to background light from the progenitor stars. The main-sequence lifetime of a star varies with its mass as  $\tau_{\text{MS}} \sim 10^{10} (M_{*}/M_{\odot})^{-2.2}$  yr (see, e.g., Mihalas & Binney 1981). All of the stars in this scenario have  $M \geq 10 M_{\odot}$ , or  $\tau_{\text{MS}} \lesssim 6 \times 10^7$  yr. The reduced opacity in low- $Z$  stars leads to higher luminosities that may shorten the lifetime estimate even further (Adams & Laughlin 1997).

We therefore expect none of these stars to be burning in the halo today. However, the luminosity from these massive stars and their deaths as SNs was very high in the past. To estimate the average luminosity from this bright phase, we can assume that the LG processed  $2 \times 10^{12} M_{\odot}$  into  $25 M_{\odot}$  stars, the median stellar mass in our IMF. Since the stellar lifetimes for the scenario depicted here are all less than a few tens of millions of years, this epoch probably did not last for more than  $\sim 1$  Gyr. The average luminosity was then about  $8 \times 10^{46} \text{ ergs s}^{-1}$ . The surface brightness associated with this luminosity over a protogalactic region of radius 1 Mpc is  $2 \times 10^{-4} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$ . For the SNs, which are created from stars up to  $60 M_{\odot}$ , the surface brightness produced, given the above assumptions, with  $L_{\text{SN}} \sim 3 \times 10^{42} \text{ ergs s}^{-1}$  for 100 days, is  $2 \times 10^{-7} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$ . The SNs are so short-lived that a time-averaged luminosity is difficult to assign; however, because of the large amount of gas and dust present in the early stages of galaxy formation, conditions may be optically thick enough to lend credence to reprocessed fluxes that are relatively steady.

To compare these surface brightnesses to current limits on background light, we assume that the luminosity from the stars and the SNs are emitted over a wavelength range of 0.05–0.5  $\mu\text{m}$ . This light will be redshifted, and for a source at redshift  $z$  the net surface brightness (over all frequencies) is dimmed by a factor of  $(1+z)^4$  (see, e.g., Peebles 1993). For light reprocessed into infrared wavelengths, we use the current limits from the Far-Infrared Absolute Spectrometer (FIRAS) and DIRBE instruments on COBE. FIRAS places a limit of  $3.4(\lambda/400 \mu\text{m})^{-3} \text{ nW m}^{-2} \text{ sr}^{-1}$  in the 400–1000  $\mu\text{m}$  range (Puget et al. 1996), or an average far-infrared background of about  $10^{-6} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$ . From Figure 3 of Kashlinsky, Mather, & Odenwald (1996, and references therein), a conservative value for the infrared background measured by DIRBE after foreground subtraction is about  $10 \text{ nW m}^{-2} \text{ sr}^{-1} \simeq 10^{-5} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}$  over wavelengths of 1.25–100  $\mu\text{m}$ . Light emitted by a source in the 0.05–0.5  $\mu\text{m}$  range would be redshifted into the DIRBE range for  $z \gtrsim 1$ ; to be detected by FIRAS, such a source would have to be at extremely high redshifts or have the stellar light undergo dust reprocessing. Comparing the surface brightness from the stellar and SNs contributions derived above with these backgrounds, we see that the light from the SNs is well below both the FIRAS and DIRBE limits, even before including the  $(1+z)^4$  dimming. For the progenitor stars, sources at redshift  $\gtrsim 1$  (3) would be compatible with the DIRBE (FIRAS) backgrounds. This assumes that the light comes directly to us, dimmed by  $(1+z)^4$ , and that dust, if present, absorbs and reradiates 100% of the source's emission; this is a reasonable upper limit to the contributions of an early epoch of intense star formation dominated by massive stars and the resulting SNs. Although the infrared backgrounds constrain any period of initial massive star formation to satisfy  $z \geq 1$  or 3, the onset of this phase could follow recombination or parallel that of galaxy formation.

We had mentioned earlier that the halo mass fraction in NSs and BHs in the Galaxy (Table 1),  $f$ , should be viewed as an upper limit since all such remnants are assumed to ultimately reside in the halos of the Galaxy and M31. One way this could happen would be if massive stars were formed in small protogalactic clumps at high redshifts and blew out their enriched ejecta through SN winds as galaxies were

assembling. The clumps would later merge, leading to present halos that contain the remnants but not the gas remaining from making them. This sequence is similar to that described in Fields et al. (1997), where the bulk of the elements were formed at  $z \sim 10$ . Alternately, this starburst phase could occur in galaxies undergoing monolithic collapse starting at  $z = 3-4$ ; the picture of an evaporating enriched hot gas component created by SNe, with remnants trapped in the largest galactic halo potentials, is still valid in the context of structure formation. In this event, dust in the host systems must be invoked as being responsible for significant extinction of this superluminous phase (see, e.g., Mushotzky et al. 1996, and references therein, for these points). After the hot ejecta have been blown out of small protogalactic clumps, or the massive protogalaxies, the gas that remains as a cold gas component could then either merge or collapse to form the disks of present-day spiral galaxies. The self-enrichment of this part of the Galaxy is a separate process from the earlier epoch of Type II enrichment that we consider.

In order to maximize the halo population of NSs and LMBHs, we focused on an early generation of massive stars. We assumed that a significant fraction of the baryons were processed through this early phase; however, it is clear that this scenario does not account for every baryon in our Galaxy. For instance, a small fraction of the total baryonic mass needs to form the disk of our Galaxy where low- and intermediate-mass stars play a crucial role. Observations of the present interstellar medium (ISM) in galaxies help quantify the role played by such stars in local chemical enrichment. For example, the relation between  $Y$  and  $Z$  satisfies  $\Delta(Y)/\Delta(Z) \sim 4 \pm 1$  (Timmes et al. 1996). From Table 2 we see that this quantity, averaged over the two values of the primordial  $Y$ , is about 5 for case 1 and 1.7 for case 2. Case 1 is consistent with the observed value, but case 2 has a somewhat low value of  $\Delta(Y)/\Delta(Z)$ . Case 2 is similar to what we would expect a priori of the yields purely from massive stars. In general, stars of mass less than  $8 M_{\odot}$  produce the bulk of the helium from stellar nucleosynthesis, while stars more massive than this produce the bulk of the metals. The critical issues in connecting the ISM abundances with those in an intragroup or intergalactic medium are the assumptions made for the star formation history and for how much early enrichment is reflected in the stars or ISM of present galaxies owing to the role played by outflows and winds. Since the stars associated with late enrichment are a small fraction of the total baryons, the gist of our conclusions should not be altered.

Other baryons we do not account for in this work are those responsible for metal-poor low-mass stars in the Galactic halo. The total mass in metal-deficient Galactic halo stars today is less than about  $10^{10} M_{\odot}$ , which is a small fraction of the material processed through the early generations of massive stars discussed here. The primordial gas reserves are not significantly decreased in forming such metal-poor stars, and those having low masses have not yet returned any material to the ISM. An understanding of the physical conditions that produced the two apparently distinct stellar populations in the Galactic disk and halo remains to be achieved.

## 5. CONCLUSIONS

We have shown that it is possible for halos with significant mass fractions in NSs and BHs to form in the LG

without necessarily overenriching the ambient gas relative to solar  ${}^4\text{He}$  and/or metal abundances if these objects were produced by an early generation of stars with initial metallicity varying between  $10^{-4} Z_{\odot}$  and 0. In such cases, these remnants contribute at most 29%–36% of the Galactic halo's dynamical mass (assumed here to be  $10^{12} M_{\odot}$ ). We find within the uncertainties in stellar structure and evolution that models for halo NSs and BHs cannot be immediately rejected on metal overproduction arguments alone because of the critical factor of the choice of progenitor metallicity in determining the yields. The constraint of final  $Z$ -values of  $Z_{\odot}$  for the ambient gas after dilution was motivated by the metallicities  $Z_X$  observed in the diffuse X-ray gas in galaxy clusters and groups, which are in the rough ballpark of solar. The baryonic requirements in Table 2 will scale as  $Z_X^{-1}$  if the dilution criterion is adjusted to other values in the range of observed X-ray gas metallicities. Furthermore, although  $Y$  is not measured in this X-ray gas, and is hence not a direct constraint, we found that  ${}^4\text{He}$  is *more* constraining than metals as far as dilution requirements are concerned for low- $Z$  massive stars' ejecta (Table 2). The more conventional picture of the extreme metal pollution from massive stars is true only for higher metallicity progenitors such as  $Z = Z_{\odot}$  stars (Table 1).

NSs make up at least 24% of the total mass fraction of these compact objects in the Galactic halo. LMBHs may be formed from stars as massive as  $40 M_{\odot}$  (WW95), as shown in Figures 1 and 2, depending on the kinetic energy chosen for launching the SN shock in high-mass stars, although we took the most conservative value for this.

The fraction of NSs and BHs in the Galaxy can be as high as the values in Table 1 by satisfying the requirement that the LG attains solar metallicity on average; a preferential loss of high-metallicity gas to the intergalactic medium need not be invoked. The most favorable case of this ( $Z_{\text{gas},f} = Z_{\odot}$ ) is for  $Z = 0$  stars, where  $f = 36\%$  (Table 1) and  $M_{\text{gas},i} = 2.4 \times 10^{12} M_{\odot}$  (Table 2). The worst case is that of the  $10^{-4} Z_{\odot}$  stars with  $Y_{\text{gas},f} = Y_{\odot}$ , where  $f = 29\%$  and  $M_{\text{gas},i} = 8.1 \times 10^{12} M_{\odot}$ . We emphasize that this derived  $f$  should be viewed as an upper limit, as we have assumed that all the remnants created in this scenario ultimately reside in galaxy halos until today. This assumption is plausible in the context of current structure formation scenarios (§ 4). However, if we were to be more democratic and preserve, on the scale of galactic halos, the global baryon to total mass ratio, then the Galaxy and M31 would each receive a fraction,  $(M_{\text{gal}}/M_{\text{LG}})*f$ , in remnants. Then  $f$  would be reduced in the “best” and “worst” cases above to about 6% and 1%, respectively.

$Z = 0$  progenitor stars have lower integrated metal yields and leave behind higher masses in remnants (Table 1), but since some self-enrichment is expected to occur in early star-forming regions, the case of  $Z = 10^{-4} Z_{\odot}$  stars is probably more realistic. This, however, needs larger baryonic masses for dilution to avoid supersolar pollution, which would require a high adopted mass for the LG as derived by Dunn & Laflamme (1993). Nevertheless, it is possible, although just barely, to reconcile the baryonic requirements set by Table 2 with big bang nucleosynthesis constraints without assuming a relative baryon concentration in the LG via cooling processes, etc. This is especially true for dilution of metal enrichment to solar levels. Other limits such as background light production are met more comfortably, as is shown in § 4. As we have discussed, the



presence of massive stars at early epochs are favorable from some aspects, but no one stellar population can explain all of the observations.

We have focused on an initial burst involving only high-mass stars in order to maximize the contribution of NSs and LMBHs to halo MACHOs, and we calculated the yields from just this epoch. In doing this, we have assumed that the baryons that form Population I and II stars are not enriched by the burst that creates the MACHOs in this scenario and leaves behind a large amount of enriched gas. This segregation is possible if galactic winds that accompany the burst phase remove associated polluted ejecta, leaving a small fraction of material behind that eventually forms disk and halo stars. The combined Population I and II baryonic mass is at most a few percent of that associated with the burst phase and will not alter the main conclusions of this paper. A similar separation in enrichment may have occurred in the case of the hot X-ray gas seen in many galaxy clusters and groups, which contains a significant fraction, and often most, of the baryons. This gas is relatively enriched in metals and coexists with galaxies containing low- $Z$  stars.

Although some recent observations have made a re-evaluation of baryonic dark matter candidates necessary, an unavoidable consequence of making a case for stellar remnants as MACHOs is that they are only a fraction of the mass processed through their parent stars, and a significant amount of enriched gas will remain. Adams & Laughlin (1996) have noted this efficiency problem in creating halo WDs, and this is especially true for NSs/BHs relative to WDs. The early generations of stars leave behind significant amounts of enriched ejecta. It is possible that much of this enriched gas escaped altogether from the Group or was ejected into intergalactic space (as suggested in Adams & Laughlin 1996 and Fields et al. 1997). Here we have shown that if we want to dilute  $Y$  or  $Z$  in the leftover gas to solar values, then the LG most likely started from a baryonic reservoir  $\geq 2 \times 10^{12} M_{\odot}$  (§ 3). We have made a plausibility case for NS/BH halos that do not leave behind over-enriched gas. However, the present uncertainties in SN yields, the mass of the LG, and the primordial  ${}^4\text{He}$  abundance could affect our results. The contribution of NS/BH remnants to galaxy halos may be smaller than those in Table 1, or the leftover intragroup gas could have lower metallicities. For progenitor metallicities  $\lesssim 10^{-4} Z_{\odot}$ , the total masses in the remnant population in our results are in the range of the experimental most likely total mass in MACHOs of  $\sim 2 \times 10^{11} M_{\odot}$ , mentioned in § 2.

It is encouraging that the metal abundance of the gas remaining after this phase of early star formation is  $Z \geq 0.3 Z_{\odot}$ , which is not in conflict with that of the intragroup gas in some groups of galaxies (Mulchaey et al. 1996). After the Group formed, a large amount of gas is leftover in this scenario. If the potential of the LG can retain this gas, it must exist in a diffuse component in the intragroup medium at temperatures of  $\sim 10^6$  K; the Group's potential is probably insufficient to heat it to keV temperatures. This is consistent with the idea put forth by Mulchaey et al. (1996) that the intragroup medium in spiral-rich groups could have  $T \sim 0.2$  keV and remain invisible to current experiments such as *ROSAT*. Studies of clusters of galaxies show that there is up to several times as much mass in just the X-ray emitting gas as the mass in the galaxies (see, e.g., Henry, Briel, & Nulsen 1993). It remains to be seen how groups of

galaxies, especially spiral-dominated ones, compare in this regard, especially if the potential of the group is not large enough to keep any gas that is present heated at keV temperatures (Mulchaey et al. 1996).

Alternatively, some of the leftover gas could be locked into faint low-mass field stars throughout the intragroup medium, or some gas may have been lost from the Group. In the latter case, the gas must remain ionized; otherwise, it would violate Gunn-Peterson constraints on the amount of intergalactic neutral hydrogen. The recent detections of  $\sim 10^6$  K gas by the *Extreme-Ultraviolet Explorer* in the directions of the Virgo and Coma clusters might prove to be important in resolving the issue of the fate of such gas in nearby systems. In the case of Virgo (Lieu et al. 1996), this gas appears to be relatively enriched ( $\sim 0.5 Z_{\odot}$ ). Another key issue is whether the elemental abundance ratios in the hot gas in clusters of galaxies indicate a Type II or Ia SN origin; at present, it is undecided. If a Type II SN origin for this gas emerges in future studies, it would certainly favor the presence of a remnant population dominated by NSs and BHs. We conclude, therefore, that most of the baryonic "dark matter" might be in cool ( $\sim 10^6$  K) gas in the LG, but we emphasize that stellar remnants in the form of MACHOs are also a significant factor in the galactic dark matter problem.

Halo BHs are not expected to be significant sources of radiation for typical halo ambient gas densities. However, BHs from this population have a local number density of  $\sim 2 \times 10^{-5} \text{ pc}^{-3}$ , assuming that they are distributed in a 100 kpc halo today. Therefore, there could be at least one such BH within a 50 pc radius from us. If it has sufficiently low velocity, it might be detected in future projects such as the Sloan Digital Sky Survey (Heckler & Kolb 1996).

As we have seen, evaluating the case for stellar remnants as MACHOs is not free of some assumptions. The IMF from which the MACHOs were created must be different from that of present galactic disks. The IMF's peak must be tailored to  $\sim 2\text{--}4 M_{\odot}$  for WDs, or to include only stars more massive than about  $10 M_{\odot}$  for NSs and BHs. Furthermore, all candidates face some critical issues. To not over-enrich the universe, some dilution of metal-rich SN ejecta must take place, and this constraint is considerably tighter for NS/BH remnants than for WDs simply because of the fraction of the progenitors that collapses into the remnant in each case. If dilution does not occur and the enriched gas is ejected from galaxies into an intracluster or intergalactic medium, strong constraints from measured iron and oxygen abundances in the intracluster medium or from the carbon enrichment in the Ly $\alpha$  forest clouds (particularly for WD models) must be considered. (See Fields, Freese, & Graff 1998 for a comprehensive discussion on the relative merits and limitations of these baryonic MACHO candidates.) The burst of intense star formation may be unobservable if it occurred at sufficiently high redshifts or if it is obscured by dust. However, halo WDs must contend with limits from the HDF, which constrains their age via their cooling emission and, with greater model dependency, the current measured rates of Type Ia SNs, while halo NSs and BHs contribute a direct signature primarily through their mass.

The MACHO experiment's results indicate that about 50% of our halo may be made of objects of mass  $\sim 0.5 M_{\odot}$  (for a "standard halo" mass of  $4 \times 10^{11} M_{\odot}$  within 50 kpc). Experiments with longer periods of observation may detect

events of longer duration. The typical MACHO mass is unlikely to be lower than the presently quoted  $0.5 M_{\odot}$ , since strong constraints placed by the MACHO and the EROS collaborations (Renault et al. 1997; Alcock et al. 1998) based on shorter timescale events have already ruled out significant populations in objects of lower masses. Also, Graff & Freese (1996a, 1996b) have ruled out significant halo mass fractions in red and brown dwarfs. Gyuk & Gates (1998) have shown that even models of rotating halos cannot lower the present experimental MACHO mass to the brown dwarf range. An increase in the average MACHO mass is, however, possible if more events of longer duration are detected with time. In fact, the MACHO candidate mass has increased over the last few years (Alcock et al. 1993, 1996, 1997). Therefore, we have considered the possibility of MACHOs in the halo of about solar and somewhat higher masses.

If such objects exist, they may be seen in the future as longer timescale events by microlensing experiments. In order to have some idea of the microlensing signature of halo NSs and BHs, we derive here some rough numbers for the MACHO experiment in particular. In this work, roughly 85% of the NS/BH remnants produced have masses  $\lesssim 5 M_{\odot}$ . The duration of a microlensing event is mass dependent; for a standard halo model, the average event timescale varies with the MACHO mass as  $\langle \hat{t} \rangle \propto (MD)^{1/2}/v \cong 140 (M/M_{\odot})^{1/2}$  days (Alcock et al. 1997) for an assumed MACHO velocity  $v$  and distance  $D$ . Thus NSs/BHs of mass  $\lesssim 5 M_{\odot}$ , if they exist in the Galactic halo, will be picked up by the MACHO experiment as events with average timescales  $\lesssim 313$  days  $\sim 0.86$  yr. A typical NS or an LMBH of mass  $\sim 1.5 M_{\odot}$  would have  $\langle \hat{t} \rangle \sim 150$  days. However, the most *probable* duration of events from  $1.5 M_{\odot}$  objects in the halo is only  $\sim 90$  days (Griest 1991). The MACHO experiment, subsequent to the 2 yr data publication, has detected a few events with durations approximately between 90 and 105 days. While this is hardly proof of the existence of halo NSs and BHs, it is worth noting in

relation to the question of how such objects would appear to microlensing experiments and whether they may have already been detected. Given our prediction of longer timescale events from halo NSs and BHs, it is provocative that the first-year data of EROS2 in the direction of the SMC give a most probable lens mass of over  $2 M_{\odot}$  if they are present in the Galactic halo (Palanque-Delabrouille et al. 1998), although self-lensing by the SMC is also a possibility. Observations of the subsequent event SMC-98-1, however, seem to imply a binary lens located in the SMC itself (see, e.g., Afonso et al. 1998).

As the final halo mass fraction in NSs/BHs in this work is less than 100%, it is not necessarily incompatible with the presence of other components that could account for the shorter duration microlensing events that are already detected. Obviously, one can only take the theory of two or more distinct halo populations to a point, beyond which the measured dynamical halo mass is exceeded. Above, we have seen an estimate of the microlensing signature from halo NSs and BHs. An alternative question is how the present microlensing data can constrain any higher mass population. In the context of the standard halo model, the data indicate a most likely lens mass of about  $0.5 M_{\odot}$ . However, the lens mass estimate depends on the phase space distribution of the lenses within the halo. To constrain any NS mass population, we must explore the parameter space for galactic halo models, given the current data. We will consider this problem in a subsequent work.

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