FURTHER CONSTRAINTS ON WHITE DWARF GALACTIC HALOS

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ABSTRACT

The suggestion that roughly half the mass of the Galactic halo might be in the form of white dwarfs, together with the limits on its mass fraction in faint red stars and on the initial metallicity of the Galactic disk, would set strong constraints on the initial mass function (IMF) of the halo. Particular IMFs have been proposed to cut off both the numbers of low-mass stars contributing to the infrared background and of high-mass stars that contribute to the growth of metallicity when they promptly explode as gravitational collapse (Type II and Type Ib/c) supernovae. Here we examine the further contribution to metallicity from Type Ia (thermonuclear) supernovae that would later be produced from the halo white dwarf population. We find that, for most of the evolutionary scenarios for the Type Ia supernova progenitor systems proposed so far, constraints on the white dwarf mass fraction in the halo from the predicted production of iron would be extremely severe. When the predicted iron excess is not so large, the exceedingly high Type Ia supernova rate predicted for the present time would also exclude a major contribution of white dwarfs to the halo mass. The white dwarf contribution, in all cases, should be below 5%–10%. Besides, for the IMFs considered, the duration of the halo burst should be shorter than 1 Gyr in order to avoid too large a spread in the iron abundances of Population II halo dwarfs, and the predicted halo [O/Fe] ratio would be at odds with observations.

Subject headings: galaxies: halos — galaxies: stellar content — supernovae: general — white dwarfs

1. INTRODUCTION

Microlensing experiments (Bennet et al. 1996; Alcock et al. 1997) might indicate that roughly half the mass in the halo of our Galaxy could be made of white dwarfs (WDs). The existence of such large numbers of WDs, the remnants of an earlier generation of halo stars, poses different problems. One of them is that, as shown, for instance, by Adams & Laughlin (1996), the initial mass function (IMF) of the parent population of those WDs should have been very different from the IMF inferred for the galactic disk (see also Chabrier, Segretain, & Méra 1997; Fields, Mathews, & Schramm 1997). Otherwise, the low-mass tail of the IMF would give red dwarfs much in excess of their maximum allowed mass fraction in the halo (Graff & Freese 1996), while the high-mass end, by its metal production, would raise the initial metallicity, Z, of the galactic disk much above any reasonable level (unless the supernova products were ejected into the intergalactic medium). Galactic halos that are far too luminous (which should be seen at high redshifts) would also result from the large numbers of massive stars. From that double constraint, Adams & Laughlin (1996) deduce that the IMF of WD progenitors should be confined within the mass range \( 1 \ M_\odot \leq M \leq 8 \ M_\odot \) and be sharply peaked about a characteristic mass of \( M_C \approx 2.3 \ M_\odot \). Even with such an IMF, because of the fact that only a fraction of the initial mass of the progenitor star stays trapped in the remnant WD, those authors (see also Isern et al. 1997) conclude that most likely the WD contribution to the halo mass should be 25% or less, 50% being an extreme upper limit. More recently, Gibson & Mould (1997) have examined the production of C, N, and O by the intermediate-mass star progenitors of the WDs. They find that the expected [C, N/O] ratios would be hard to reconcile with those measured in Population II halo dwarfs.

Difficulties with models of WD-dominated halos are also pointed out by Venkatesan, Olinto, & Truran (1997). Earlier, Charlot & Silk (1995) had set upper limits to the WD fraction in galactic halos from the absence of the luminosity signature of the WD progenitors in deep galaxy surveys. It should be stressed that mass determinations from gravitational microlensing are still uncertain (Mao & Paczyński 1996; Venkatesan et al. 1997). Thus, possible incompatibilities with observational constraints must be taken into account before concluding that star formation in the halo should have been very different from that inferred for the disk.

In this Letter we look further into the problem of the metal enrichment of the Galactic disk and halo by the putative parent population of WDs. Massive stars (\( M \gtrsim 8–10 \ M_\odot \)) eject metals mostly at the end of their lives, when they explode as supernovae (SNs) because of the gravitational collapse of their dense, fuel-exhausted cores. Phenomenologically, those are Type II (hydrogen-rich) and Type Ib/Ic (hydrogen-devoid) supernovae. Their progenitors are basically eliminated by adopting the IMF proposed by the aforementioned authors. However, the very population of halo WDs should give rise to another type of supernovae: thermonuclear supernovae (phenomenologically Type Ia, lacking hydrogen in their spectra). Type Ia supernovae are the explosions of some WDs (among those made of C+O) that ignite when they are compressed by mass accretion from a close binary companion. Those explosions yield an average of \( \sim 0.6 \ M_\odot \) of iron, and it is estimated that they produce about \( \frac{2}{3} \) of the iron in the galactic disk (Bravo et al. 1993; Woosley & Weaver 1994), the other \( \frac{1}{3} \) coming from gravitational collapse supernovae. Therefore, unless the binary frequency in the halo is very low and/or the distribution of initial binary parameters (mass ratios of the two components, binary periods) in the progenitor population of the halo WDs strongly suppresses the formation of close binary systems containing C+O WDs, one should expect a large contribution to the iron contents of the disk from a massive WD halo.

In the following, we derive the time evolution of the iron mass produced by Type Ia SNs after an initial burst of star...
formation able to generate the presumptive WD halo population without violating either the red dwarf or the high-mass star constraints. Whereas the gravitational collapse supernova rate can just be set equal to the massive star formation rate, the thermonuclear supernova (Type Ia) rate depends on the evolutionary path assumed to produce the supernovae from a fraction of the close binary systems containing C+O WDs, together with the adopted distributions of initial binary parameters. We will thus discuss the dependence of those hypotheses of the iron production constraint on the mass fraction of WDs in the halo. We will see that in most cases the iron enrichment from Type Ia SNs would be incompatible with a substantial contribution of WDs to the halo dark matter. In the remaining cases, the exceedingly high Type Ia SN rate predicted for the present time also indicates that the mass fraction of the Galactic halo in the form of WDs should be much smaller than that suggested from microclensing experiments. A further restriction to the hypothesis of particular IMFs giving rise to a large halo WD population comes from the comparison of the predicted spread in iron abundances and the inferred [O/Fe] ratios for Population II halo dwarfs with observational data.

2. Modeling, Results, and Discussion

We will assume that the parent population of the halo WDs forms in a burst lasting ~1 Gyr, with an IMF of the form

\[ \ln f(\ln M) = A - \frac{1}{2(\sigma)^2} \left[ \ln \left( \frac{M}{M_b} \right) \right]^2, \tag{1} \]

where \( A, M_b, \) and \( \sigma \) are constants (Adams & Laughlin 1996). \( A \) sets the total mass in the burst, and for \( M_b \), the mass scale of the distribution, and \( \sigma \), its dimensionless width, the values \( M_b = 2.3 \, M_\odot \) and \( \sigma = 2.3 \) are adopted. The IMFs proposed by Chabrier et al. (1997) and by Fields et al. (1997) are similar and, for our present purpose, give equivalent results.

A fraction of the halo stars will be in binary systems whose initial parameters (primary mass, secondary/binary mass ratio, and separation between the two components) imply that they should eventually end up as a C+O WD and a close companion. Mass transfer from the companion to the WD can then lead to explosive C ignition and a Type Ia SN. Different scenarios have been proposed, depending on the nature of the companion (another C+O WD, an He star, a subgiant or red-giant star). We have considered all of them in order to calculate the Type Ia SN rates and corresponding iron production following an outburst of star formation. Namely, the scenarios are (a) merging of a couple of C+O WDs (double-degenerate merging [DD]), (b) explosive ignition of He (followed by central ignition of C) at the surface of a C+O WD as a result of accretion from an He star companion (helium cataclysmic variable [HeCV]), (c) central explosive ignition of C as a result of mass growth by accretion from a red-(sub)giant companion (cataclysmic-like system [CLS]), (d) same as the previous case, but allowing higher mass-loss rates from the companion (“wind solution” [CLS(W)]), and (e) explosive ignition of He (produced from burning of H) at the surface of a C+O WD accreting mass from the wind of a red-giant or supergiant companion (symbiotic system [SS]). In scenarios a, c, and d, the exploding WD has reached the Chandrasekhar mass, while in scenarios b and e, the explosion takes place when a thick enough He layer has accumulated, the C+O WD mass still being below the Chandrasekhar mass. Most of these scenarios were proposed in a seminal paper by Iben & Tutukov (1984; see Iben 1997 for a recent review). The wind solution for the CLS scenario was proposed by Hachisu, Kato, & Nomoto (1996). The characterization of the different Type Ia SN scenarios considered here is as in Ruiz-Lapuente, Burkert, & Canal (1995) and Canal, Ruiz-Lapuente, & Burkert (1996; see also Ruiz-Lapuente, Canal, & Burkert 1997). The results reported here correspond to the distributions of initial binary parameters adopted in those papers. We have also explored other suggested distributions, but the outcome was not significantly different.

In Figure 1 we show the growth of the iron mass, \( M_{Fe} \), following the halo star formation outburst, for scenarios a–e. We first assume that all the iron produced by the Type Ia SNs in the halo directly mixes with the gas in the disk, and we later discuss the possibilities of relaxing this hypothesis. The halo mass adopted is \( M_{halo} = 10^{12} M_\odot \) (its dynamical mass; see Peebles 1995). We take the disk mass to be \( M_{disk} = 0.1 \times M_{halo} \). The relevant quantity, for our purpose, is the ratio \( M_{Fe}/M_{disk} \), that is, the \( Z_{Fe} \) in the disk resulting from the halo contribution. As we see in Figure 1, in all scenarios \( M_{Fe} \) grows with time until reaching a maximum value at an epoch that corresponds to the explosion of the most slowly evolving Type Ia SN progenitors formed in the halo outburst. The plateau value and the time at which it is reached depend on the scenario. As a conservative upper limit to the initial \( Z_{Fe} \) in the Galactic disk, we take half its solar value, \( Z_{Fe,solar} = 1.7 \times 10^{-3} \) (Cameron 1982). Thus, \( Z_{Fe}(0) \lesssim 8.5 \times 10^{-4} \). For our disk mass, that corresponds to \( M_{Fe} = 8.5 \times 10^7 M_\odot \). Such a value is shown by the dashed line in the panels of Figure 1.

We see that unless most of the iron produced by Type Ia SNs from the halo WD population does not fall into the disk, in three of the scenarios considered [HeCV, CLS, and CLS(W)]
the upper limit would already be reached at the end of the outburst (and even before that in the HeCV scenario), with the iron mass rapidly growing to much larger values afterward. In the SS scenario, the limit would be reached at $t = 0.5$ Gyr after the end of the burst. Later, much larger iron masses are produced (it must be noted that the Type Ia SN rates have been very conservatively calculated here: the SS efficiency in producing Type Ia SNs has been set to its lowest estimate). Only in the DD scenario would the upper limit not be reached until $t=1.5$ Gyr after the end of the burst, to slowly grow to $t=1.7$ times that value 10.5 Gyr later. The reason for the comparatively low Type Ia SN rates in this scenario is that most of the progenitors of the DD mergers are within the initial mass range $6 M_\odot \leq M \leq 8 M_\odot$, which is not favored by an IMF of the form given in equation (1). Note that for longer delays between halo and disk formation, the initial iron abundances in the disk would be higher.

In fact, the halo Type Ia SN contribution to the iron enrichment of the disk would still have been dominant at the time of the birth of the Sun. Therefore, even neglecting the contribution from Type Ia SNs and gravitational collapse supernovae in the disk (and the decrease in its gas contents due to previous star formation), the WD mass fraction in the halo should be $\leq 5\%-10\%$ [for the HeCV, CLS, and CLS(W) scenarios]. From the iron argument alone, up to $\approx 20\%$ would still be compatible with the SS prediction, and that for the DD scenario might even fit the microlensing estimate. However, as we will see next, consideration of the predicted Type Ia SN rates for the present time sets more restrictive bounds.

Type Ia SN rates.—It is interesting to note that, in the DD and SS scenarios, Type Ia SNs should still be exploding in the halo at $t = 13$ Gyr after the start of the initial outburst. In the DD scenario, the rate would be $v_{\text{SN, Ia}} \approx 7 \times 10^{-3}$ yr$^{-1}$, whereas in the SS scenario it would be $v_{\text{SN, Ia}} \approx 2 \times 10^{-2}$ yr$^{-1}$. Even at $t = 18$ Gyr (a halo age suggested by Chabrier et al. 1997), $v_{\text{SN, Ia}} \approx 4 \times 10^{-3}$ yr$^{-1}$ in the DD scenario and $\approx 1 \times 10^{-2}$ yr$^{-1}$ in the SS. All those values are far above observational upper limits. The only supernovae observed in our Galaxy in the last 1000 yr that clearly were Type Ia SNs have been SN 1006 and SN 1572 (van den Bergh & Tammann 1991), and their progenitors did not belong to the halo population. The argument that the historical supernova sample is not complete beyond a distance of $\sim 3$ kpc applies to the thick disk population at most, but not to typical halo objects. Even at a distance of $d \sim 20$ kpc (i.e., far out in the halo from our location in the Galaxy) the apparent blue magnitude of a Type Ia SN at maximum would still be $m_b = 2.5$ (about 1 mag brighter than Sirius). From this argument, a reasonable upper limit to the halo Type Ia SN rate should be at least 1 order of magnitude below that predicted by the DD scenario, which would again put the contribution of the WD population to the halo mass below $5\%-10\%$. Consideration of the rate of merging of WD pairs in the halo population strengthens this conclusion, since it should occur at rates of $n_{\text{merg}} \approx 0.4$ yr$^{-1}$ (13 Gyr) or $\approx 0.3$ yr$^{-1}$ (18 Gyr). Most of them would not produce any Type Ia SNs but a hot WD, which would remain very luminous for $\sim 10^8$ yr. Their total population should thus be $\sim 3-4 \times 10^7$ nowadays, and it would hardly have escaped detection.

The halo gas component.—In the preceding we have assumed that most of the material ejected by Type Ia SNs mixes with the gas in the Galactic disk. If the halo were left completely gas-free after the initial burst of star formation, one would expect that roughly half the Type Ia SN ejecta would escape the Galaxy, whereas the other half would hit the disk and mix with the gas there (typical velocities of the ejecta are larger than the escape velocity from the Galactic halo, and there would not be halo gas to slow them down). However, as pointed out by Adams & Laughlin (1996), Isern et al. (1997), and Gibson & Mould (1997), the intermediate-mass star progenitors of the WDs should return typically $\approx 50\%-75\%$ of their mass to the interstellar medium through stellar winds and planetary nebula ejection. The timescale of such mass ejection is shorter than that of growth of the iron mass from Type Ia SNs (especially in the DD and SS scenarios). Therefore, much of this gas should mix with the iron-rich Type Ia SN ejecta. In that case, the iron would be much more diluted than if it were mixed with only the gas in the disk. There is, however, the problem of where this halo gas might be hidden (it cannot fall into the disk, since otherwise the latter would be much more massive than it actually is). One possibility is that it would be concentrated into cold molecular clouds (De Paolis et al. 1997). In that case, since formation of most clouds would precede ejection by Type Ia SNs of a major fraction of the iron mass and the filling factor of the clouds should be small, the case would resemble that of a gas-free halo. Another possibility is that heating of the halo gas by Type Ia SN explosions might be enough to generate a strong galactic wind and eject most of the gas. A first estimate of the energy budget shows that this possibility is only marginal. To summarize, the problem of the halo gas component, instead of raising the upper limit to the WD mass in the Galactic halo, strengthens the conclusion that it should be smaller than the total mass in the Galactic disk and make up only $\leq 5\%-10\%$ of the halo mass.

Halo dwarf metallicities and [O/Fe] ratios.—As can be seen in Figure 1, even in a burst of star formation lasting $\sim 1$ Gyr, there should be an appreciable variation in the iron content of the gas from the beginning to the end of the burst, because of the Type Ia SNs exploding during this time interval. That should translate into a range of abundances of $\text{[Fe/H]}$ in the halo Population II dwarfs. The predicted range will depend on the duration of the burst, on the time variation of the star formation rate within the burst, and on the Type Ia SN scenario. In Figure 2 we compare the growth with time of iron abundance for the stars formed in the halo burst (lasting 1 Gyr) among scenarios a–e considered above, assuming a constant star formation rate. We see that, for any scenario, a significant spread in iron abundances among halo dwarfs should be expected. A fraction of dwarfs would show near-solar iron abundances (and even higher, for the HeCV scenario). The measured spread is $\Delta [\text{Fe/H}] \approx 0.5$, which is not favored by an IMF of the form given in equation (1). Agreement could be obtained in all cases by shortening the duration of the burst, but that would be in conflict with evidence of a scatter of $\sim 2-3$ Gyr in the ages of those stars (Schuster & Nissen 1989). A more difficult problem is that Type Ia SN explosions alone would always give $[\text{O/Fe}] = -1.4$ ($-1$ being an extreme upper limit), while the observed $[\text{O/Fe}]$ in halo dwarfs is $\geq 0.5$ (and thus bears the signature of massive star nucleosynthesis: Barbuy 1988; Abia & Rebolo 1989; Spite & Spite 1991; Spiesman & Wailerstein 1991). Therefore, not only should the duration of the halo burst be extremely short to avoid contamination by Type Ia SN products, but, in addition, an even earlier generation of massive stars should have produced the $[\text{O/Fe}]$ actually measured. That appears unlikely.

3. Conclusions

If a large fraction of the Galactic halo mass were made of WDs, one would expect a large iron production from Type Ia SNs arising from a fraction of the WDs belonging to close binary systems. Since both the total iron yield and its time
evolution depend on the evolution assumed for Type Ia SN progenitors, we have considered all the main Type Ia SN scenarios proposed so far: double degenerate merging, He-star cataclysmic systems, two different versions of the cataclysmic-like scenario, and symbiotic systems. The results for each evolutionary path are fairly insensitive to the choices of the initial binary parameters (distribution of mass ratios of the secondary to the primary, distribution of initial separations). The IMF is chosen to minimize the numbers of both red dwarfs and high-mass stars.

Assuming that most of the iron produced by Type Ia SNs in the halo mixes with the gas in the disk, the constraint that $Z_{Fe}$ at the time of birth of the Sun should not exceed $Z_{Fe}(<1$ Gyr) sets upper limits of $\approx 5\%$--$10\%$ to the WD mass fraction in the halo for the HeCV, CLS, and CLS(W) scenarios. Comparison of the predicted Type Ia SN rates for the present time with observational upper limits sets similar bounds for the SS and DD scenarios. Besides, a halo burst with IMFs such as those tested here would produce too large a spread in the iron abundances of Population II halo dwarfs unless it lasted less than 1 Gyr, which would conflict with evidence of a wider range of ages among those stars. Worse still, the O/Fe ratio should be far below the solar, while the measured ratio is much larger than the solar, as one would expect from massive star nucleosynthesis, and that hardly fits with the proposed halo IMFs.

Consideration of the role that Type Ia SNs that originated in the halo WD population would play in the evolution of the Galaxy thus points in the same direction as that of the fate of the gas ejected by the WD progenitors (Adams & Laughlin 1996; Isern et al. 1997) and that of the [C, N/O] ratios that would result (Gibson & Mould 1997): the WD mass fraction in the Galactic halo should be much lower than that suggested from microlensing experiments. Our derived upper bounds are even lower than those set from number counts in deep galaxy surveys.

As a more general conclusion, we can say that the proposal of ad hoc IMFs to explain a presumptive huge halo WD population poses problems that could be solved only by assuming that the whole process of star formation (single as well as binary stars) in the galactic halo has been completely different from all we know from local observations. Since the existence of a massive WD halo is by no means firmly established, it is premature to make so many ad hoc assumptions.

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