Spectroscopically Peculiar Type Ia Supernovae and Implications for Progenitors

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ABSTRACT. In a recent paper Li et al. reported that 36% of 45 Type Ia supernovae (SNe Ia) discovered since 1997 in two volume-limited supernova searches were spectroscopically peculiar, and they suggested that because this peculiarity rate is higher than that reported for an earlier observational sample by Branch et al., it is now more likely that SNe Ia are produced by more than one kind of progenitor. In this paper I discuss and clarify the differences between the results of Li et al. and Branch et al., and I suggest that multiple-progenitor systems are now less likely than they were before.

1. INTRODUCTION

In a recent paper Li et al. (2000, hereafter Li00) reported that 36% of 45 Type Ia supernovae (SNe Ia) discovered since 1997 in two volume-limited supernova searches were spectroscopically peculiar. They concluded that because this peculiarity rate is higher than the 13%–17% peculiarity rate reported for an earlier observational sample by Branch, Fisher, & Nugent (1993, hereafter BFN), it is now more likely than it was before that SNe Ia are produced by more than one kind of progenitor (e.g., both single-degenerate and double-degenerate binary systems). My purpose in this paper is to discuss and clarify the differences between the results of Li00 and BFN and to suggest that the results of Li00, together with some other recent results, make multiple-progenitor systems less likely than before.

2. THE BFN AND LI00 RESULTS

2.1. Old Results: BFN

BFN defined a normal SN Ia to be one whose optical spectra resemble those of SNe 1981B, 1989B, 1992A, and 1972E. (For plots of spectra and references to the original observational papers see BFN, and for a good general review of supernova spectra see Filippenko 1997.) Near the time of maximum light, normal SNe Ia have deep absorption features near 6150 Å due to Si ii λ6355 and near 3750 Å due to Ca ii λ3945 and other features that are produced by lines of O i, Mg ii, Si ii, S ii, Ca ii, and Co ii. For weeks after maximum, the Si ii λ6150 and Ca ii λ3750 absorptions remain strong, as Fe ii lines make their appearance.

A spectroscopically peculiar SN Ia was defined to be one that has different spectral features (not just different expansion velocities). At that time there were three well-observed examples: SNe 1991T, 1991bg, and 1986G. Near the time of maximum light SN 1991T was strikingly peculiar in having prominent features of Fe ii and hardly any signs of Si ii, S ii, and Ca ii. (The spectrum obtained closest to maximum light actually was obtained 3 days before maximum.) By a week after maximum the usual Si ii, S ii, and Ca ii features had developed, but they were weaker than in a normal SN Ia. By 3 weeks after maximum the spectrum of SN 1991T looked almost normal.

The most conspicuous peculiarity of SN 1991bg was the presence of a broad absorption trough extending from about 4150 to 4400 Å, due to a blend of Ti ii lines. The spectroscopic peculiarities of SN 1986G were like those of SN 1991bg but less extreme.

BFN inspected all available spectra of SNe Ia and attempted to subclassify them either as normal or like SN 1991T, or SN 1991bg, or SN 1986G. (In this paper, for consistency with Li00, events like SN 1991bg and 1986G will be counted together and referred to as SN 1991bg–like.) For 83 events BFN offered a least a partial subclassification; i.e., for some events it was possible to exclude some but not all of the peculiar categories. For example, for 12 events the SN 1991bg category could be excluded, but because the first spectrum was obtained too long after maximum light and/or the quality of the spectrum was insufficient, the SN 1991T category was not ruled out. Such events were not counted as normal. Of the 44 events for which BFN did offer a full subclassification, 39 (89%) were normal and five (11%) were peculiar. (The peculiar events were the three prototypes plus SNe 1957A and 1960H, both of which were found to be SN 1991bg–like.) If three additional events that were suspected of peculiarity were counted as peculiar, then 83% were normal and 17% were peculiar. (These three were SN 1988G, suspected of being SN 1991T-like, and SNe 1980I and 1971I, both suspected of being SN 1991bg–like.)

BFN assumed that the observational sample that they were working with (whatever was available) was more like a magnitude-limited sample than like a volume-limited one, so it was likely to be strongly biased against the subluminous
SN 1991bg–like events. They suggested that SN 1991bg–like events are perhaps not all that rare compared to the bright, observationally conspicuous events that are called normal.

2.2. New Results: Li00

The results of Li00 are based on intensive supernova searches characterized by such small time baselines and deep limiting magnitudes that, as shown by Li, Filippenko, & Riess (2000), they are essentially volume-limited searches as far as SNe Ia are concerned. This means that Li00 were able to probe the true fraction of the SN 1991bg–like events. Of the 45 events in their sample, Li00 found seven to be SN 1991bg–like, compared to four to six such events in the BFN sample. Evidently the SN 1991bg–like events are not as common as BFN expected. In hindsight, the reason may be that the BFN sample contains relatively few of these events while Li00 did not identify any.

Li00 found just one definite SN 1991T–like event, SN 1997br, the extensive observations of which were presented and discussed by Li et al. (1999). However, Li00 also found something quite new and interesting—SN 1999aa. Li00 showed that 1 day before the time of maximum light the spectrum of SN 1999aa was that of a normal SN Ia, but 7 days before maximum it resembled SN 1991T in having conspicuous Fe ii features and a weak Si ii λ6150 absorption while at the same time resembling normal SNe Ia in having a fairly strong Ca ii λ3750 absorption. Li00 found six SN 1999aa–like events (Li00 designated them as SN 1991Ta, and counted them as SN 1991T–like events, but for what follows in this paper they must be considered separately) and two events that could have been either SN 1991T–like or SN 1999aa–like. Clearly there is no conflict between the one to three genuinely SN 1991T–like events in the Li00 sample and the one to two such events in the BFN sample. The one significant difference between the results of Li00 and BFN is that Li00 found from six to eight SN 1999aa–like events while BFN did not identify any.

Li00 suggested that they found a higher SN 1991T–like fraction than BFN because of an age bias; i.e., if the first spectrum was obtained too long after maximum light, an SN 1991T–like peculiarity would have been difficult to see, so the SN Ia was erroneously subclassified as normal. In principle, this age bias should not apply to SN 1991T–like events in the BFN sample because if BFN thought that the first spectrum was too late to show a SN 1991T peculiarity, they did not subclassify it as normal. And, as we have just seen, there is no conflict between Li00 and BFN about SN 1991T–like events that needs to be explained.

However, the age bias certainly applied to SN 1999aa–like events in the BFN sample (see below). In fact, as Li00 discuss, even their results are affected by an age bias against SN 1999aa–like events. According to Table 1 of Li00, 19 of the 29 SNe Ia that they subclassified as normal were first observed spectroscopically near or after the time of maximum brightness. If SN 1999aa–like events are to be counted as peculiar, these 19 events should not have been subclassified as normal because some of them may have been SN 1999aa–like. Among those events for which an SN 1999aa–like peculiarity could have been detected—e.g., those observed at least 6 days before maximum, 11 were normal, five were SN 1999aa–like, three were SN 1991bg–like, and one was SN 1991T–like, i.e., 45% were peculiar! (And “peculiar” begins to sound like an inappropriate term.)

2.3. The BFN Sample Revisited

In view of the Li00 results I looked again at the BFN sample. First, although there is no conflict between the results of Li00 and BFN for SN 1991T–like events, I checked on whether the age bias could have been a significant factor for SN 1991T–like events. In the BFN sample 39 events were subclassified as normal. For about two-thirds of these there is clear evidence that they were not SN 1991T–like. For some of the others, especially those that were not observed spectroscopically before a week after maximum brightness, the case that they were not SN 1991T–like, although reasonably convincing to BFN, might not be convincing to others. (In a few cases, e.g., SNe 1981F and 1988B, the evidence is not now convincing to me.) Thus the age bias may have had a significant effect on the BFN results in the sense that if fewer events had been subclassified as normal, the peculiarity fraction would have come out to be higher.

For the SN 1999aa–like events the age bias was much more important. Only five of the 39 SNe Ia that BFN subclassified as normal were observed as early as 6 days before the time of maximum light—SNe 1974G, 1984A, 1989B, 1990N, and 1992A. All five of these were normal; none was SN 1999aa–like. Between the times of the BFN sample, which extended only to SN 1992A, and the Li00 sample, which began with SN 1997Y, SNe 1994D (Patat et al. 1996; Meikle et al. 1996; Filippenko 1997) and 1996X (Salvo et al. 2000) also were observed well before maximum light, and they too were normal, not SN 1999aa–like. The difference between this and the fact that, among the SNe Ia of Li00 that were observed 6 or more days before maximum, there were five SN 1999aa–like events versus 11 normal events can only be attributed to small number statistics. Many more good premaximum spectra of SNe Ia are needed, to find out just how common the SN 1999aa–like events really are, and to determine whether or not there is a continuous range of spectral characteristics among SNe Ia at such early times.
3. IMPLICATIONS FOR PROGENITORS

The issue of whether SNe Ia are produced by single-degenerate or double-degenerate binary systems, or both, is still open, and the issue of whether SNe Ia come from carbon igniters or helium igniters, or both, is perhaps still not closed. (For explanations of these terms and a review of SN Ia progenitor candidates see, e.g., Branch et al. 1995.) Li00 argued that the higher the peculiarity rate of SNe Ia, the more likely it is that multiple progenitors produce SNe Ia. This is a significant conclusion because it may tend to erode astronomers’ confidence in using SNe Ia as distance indicators at high redshift (the progenitor mix would evolve), and it could even have a bearing on the success or failure of proposals for more ambitious searches for high-redshift SNe Ia.

I suggest that the results of Li00 do not make multiple progenitors more likely now than they were before. First, in a general sense, the sheer relative numbers of peculiar events do not tell us whether multiple progenitors are involved or not—only inferences from the observations about the physical links, or lack thereof, between the various SN Ia subclasses can do that. More specifically, the fact that a genuinely volume-limited sample contains a higher fraction of SN 1991bg–like events than the BFN sample was expected, so it has no new implications for multiple progenitors. And as we have seen, the fraction of SN 1991T–like events in the Li00 and BFN samples are similar. The one important difference between the Li00 and BFN results is the discovery by Li00 of the SN 1999aa–like events—and if, as mentioned by Li00, they appear to be a missing link between normal SNe Ia and SN 1991T–like events, then the SN 1999aa–like events make multiple progenitors seem less likely than before.

Physical considerations do make the SN 1999aa–like events appear to be unifying. The spectroscopic differences among SNe Ia at early times are caused primarily by temperature differences (Mazzali et al. 1993; Nugent et al. 1995; Hatano et al. 1999), with abundance differences playing a secondary role (and thus being difficult to establish). A sufficiently low temperature leads to Ti ii lines. A sufficiently high temperature leads to Fe iii lines and the weakness or absence of Si ii and Ca ii lines. The SN 1999aa–like events, which have both Fe iii and Ca ii lines a week before maximum light and normal spectra by the time of maximum light, appear to connect the SN 1991T–like events with normal SNe Ia.

Another recent development makes it less likely that SN 1991T was physically distinct from normal SNe Ia. Fisher et al. (1999) found that SN 1991T was too luminous to have been produced by a Chandrasekhar-mass explosion and therefore suggested that it must have been a super-Chandrasekhar product of a double-degenerate progenitor. Fisher et al. assumed that the distance to NGC 4527, the parent galaxy of SN 1991T, is $16.4 \pm 1.0$ Mpc, on the basis of Cepheid-derived distances to NGC 4536 and NGC 4496A, which appear to be members of the same small group of galaxies as NGC 4527. However, from a simple model of the polarized dust echo of SN 1991T, Sparks et al. (1999) have estimated an upper limit to NGC 4527 of 15 Mpc, and from Cepheids in NGC 4527, Saha et al. (2000) find $14.1 \pm 0.8 \pm 0.8$ Mpc. The reduction in the distance to NGC 4527, if correct, leaves SN 1991T somewhat overluminous for an SN Ia, but it weakens the argument for super–Chandrasekhar-mass ejection and a double-degenerate progenitor. Whether a SN 1991T–like event in the Hubble flow will prove to be too luminous for Chandrasekhar-mass ejection remains to be seen.

Other recent developments have favored the view that most and perhaps all SNe Ia are carbon igniters in single-degenerate systems, with Chandrasekhar-mass ejection (see Livio 2000 and Nomoto 2000 for reviews; Langer et al. 2000, Khokhlov 2000, and Ruiz-Lapuente & Canal 2000 for further important developments; and Branch 2001 for a recent review). In this case the observational diversity of SNe Ia would be caused primarily by differences in the ejected mass of $^{56}$Ni (which controls the temperature and the peak luminosity), secondarily by differences in the amount of mass that is ejected at high velocity (differences that may indicate that two modes of burning propagation—deflagrations and delayed detonations—are involved; Hatano et al. 2000; Lentz et al. 2001), and to a lesser extent by differences in progenitor metallicity (Lentz et al. 2000) and perhaps some other things.

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