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Exclusion of a luminous red giant as a companion star to the progenitor of supernova SN 2011fe

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Type Ia supernovae are thought to result from a thermonuclear explosion of an accreting white dwarf in a binary system[1,2], but little is known of the precise nature of the companion star and the physical properties of the progenitor system. There are two classes of models[1,3]: double-degenerate (involving two white dwarfs in a close binary system[2,4]) and single-degenerate models[5,6]. In the latter, the primary white dwarf accretes material from a secondary companion until conditions are such that carbon ignites, at a mass of 1.38 times the mass of the Sun. The type Ia supernova SN 2011fe was recently detected in a nearby galaxy[7]. Here we report an analysis of archival images of the location of SN 2011fe. The luminosity of the progenitor system (especially the companion star) is 10–100 times fainter than previous limits on other type Ia supernova progenitor systems[8–10], allowing us to rule out luminous red giants and almost all helium stars as the mass-donating companion to the exploding white dwarf.

In a double-degenerate model, the orbit of the two white dwarfs shrinks owing to the release of gravitational radiation[2,4]. Ultimately, the lighter object (the secondary) is disrupted and accretion onto the primary ignites runaway thermonuclear fusion. Different single-degenerate models can be distinguished by the nature of the secondary: the white dwarf can accrete either from a wind (the "symbiotic channel"[11]), by Rochelobe overflow (the "RLOF channel"[12]), or by mass transfer from a helium star (the "helium-star channel"[1,13,14]). The secondary star in the symbiotic channel is often a red-giant star, and it is often a subgiant or main-sequence star in the RLOF channel.

We have analysed the available Hubble Space Telescope observations of the nearby galaxy Messier 101 (M101; see Supplementary Information). To pinpoint the precise supernova location in the Hubble Space Telescope images, we obtained a mosaic image of the field of SN 2011fe with the Near-Infrared Camera 2 (NIRC2) mounted behind the adaptive optics system on the Keck II telescope[15]. The Keck adaptive optics image was astrometrically registered to the Hubble Space Telescope/Advanced Camera for Surveys images, yielding a 1σ precision of $0.021''$ (or 21 mas) for the supernova position (see Supplementary Information). Figure 1 shows the site of SN 2011fe at different scales. No object is detected at the nominal supernova location in four different Hubble Space Telescope filters, or within the approximately 8σ error radius.

This nondetection can be directly translated into limits on the progenitor system brightness and temperature. Indeed, each of the four Hubble Space Telescope bands places different limits on the progenitor brightness depending on the (unknown) effective temperature and luminosity class. Figure 2 shows the region in effective temperature versus absolute V-band magnitude excluded by the Hubble Space Telescope imaging analysis (see Supplementary Information). At 3,000 K, progenitor systems of SN 2011fe are excluded for V-band absolute magnitude $M_V \leq 1$ mag, and for effective temperatures larger than 5,000 K, the exclusion is $M_V \leq -0.5$ mag. These limits rule out a symbiotic binary progenitor with brightness and colour similar to the well-observed Galactic systems RS Ophiuchi (RS Oph) and probably T Coronae Borealis (T CrB). Both of these binary systems have been advanced as possible prototypes of type Ia supernova progenitor systems[16]. Similarly, the helium-star binary V445 Puppis (V445 Pup)[17] is excluded, although the entire He-star channel cannot be completely ruled out (see the blue-shaded area in Fig. 2). In contrast, RLOF from a main-sequence or subgiant star such as U Scorpii (U Sco)[18] can easily be reconciled with the Hubble Space Telescope constraints. Finally, all variations of the double-degenerate model are consistent with the nondetection of a source at the position of SN 2011fe, because the model does not predict a bright source in the visible range. The brightness limits we have deduced also rule out a globular cluster, or any open star cluster with more than about 300 members, as the site of SN 2011fe. In addition, Fig. 2 shows that a mass donor with an effective temperature less than 4,800 K (spectral type redder than about G5) needs to have a zero-age main-sequence mass less than $2.2M_\odot$, where $M_\odot$ is the mass of the Sun. For stars with spectral type redder than an A0 star (effective temperature about 10,000 K), the companion star would need to be less massive than $3.5M_\odot$.

The single-degenerate models predict episodes of nondestructive eruptions (novae) in the decades leading up to the supernova explosion. Indeed, RS Oph, T CrB and U Sco are all recurrent novae in the Milky Way. The recurrence time of white-dwarf binaries where the white dwarfs are close to the Chandrasekhar mass is expected[19] to be 10–20 years. Although our historical images had sufficient sensitivity to detect classical novae, we find no evidence for any such outburst in the past 12 years at the site of SN 2011fe. However, we estimate an approximately 37% chance that a typical nova could have occurred in the past 5 years and have been missed given the particular cadence of the imaging (see Supplementary Information).

Historical imaging at other wavebands complements these visible-light progenitor system constraints. We have analysed 11 epochs of

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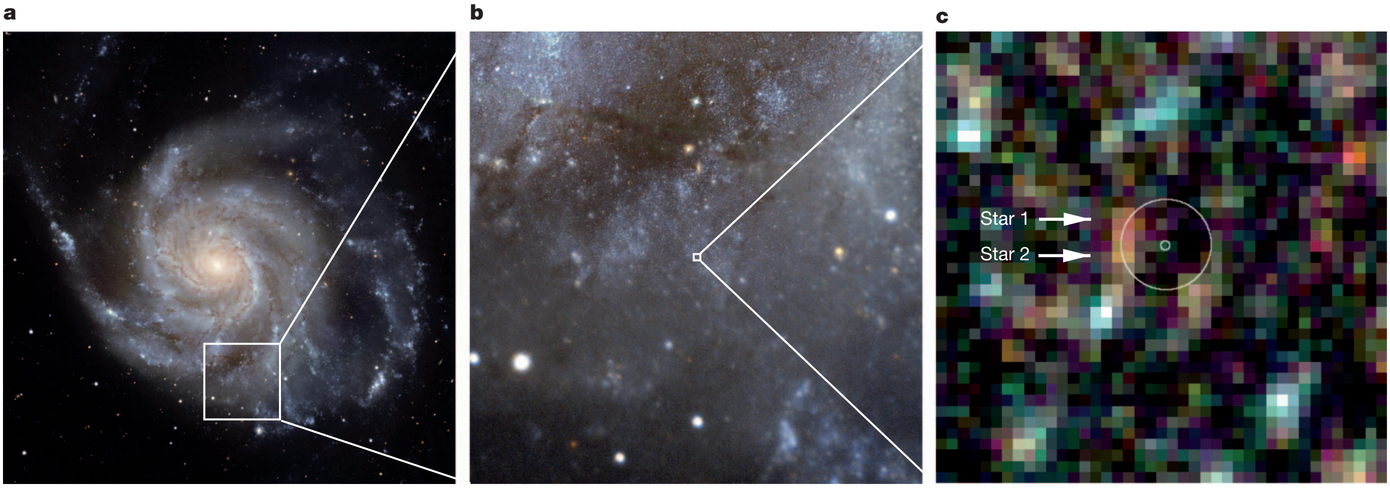

Figure 1 | The site of SN 2011fe in galaxy M101 as imaged by the Hubble Space Telescope/Advanced Camera for Surveys. **a**, A full-view colour picture of the face-on spiral galaxy M101 (18′ × 18′ field of view) constructed from the three-colour Hubble Space Telescope/Advanced Camera for Surveys images taken at multiple mosaic pointings. North is up and east to the left. M101 displays several well-defined spiral arms. With a diameter of 170,000 light years, M101 is nearly twice the size of our Milky Way Galaxy, and is estimated to contain at least one trillion stars. **b**, A cutout section (3′ × 3′) of **a**, centred on the supernova location. SN 2011fe is spatially projected on a prominent spiral arm. **c**, A cutout section (2″ × 2″) of **b** centred on the supernova location, which is marked by two circles. The smaller circle has a radius of our 1σ astrometric uncertainty (21 mas), and the bigger circle has a radius of nine times that. No object is detected at the nominal supernova location, or within the 8σ error radius. Two nearby red sources are labelled 'Star 1' and 'Star 2'; they are displaced from our nominal supernova location by about 9σ, and hence are formally excluded as viable candidate objects involved in the progenitor system of SN 2011fe. Credit for the colour picture in **a** (from http://hubblesite.org): NASA, ESA, K. Kuntz (JHU), F. Bresolin (University of Hawaii), J. Trauger (Jet Propulsion Lab), J. Mould (NOAO), Y.-H. Chu (University of Illinois, Urbana) and STScl.

archival Chandra X-ray observations of M101 taken in 2004 (see Supplementary Information), and derived upper limits for the X-ray luminosity at the location of SN 2011fe in the range $(4\text{–}25) \times 10^{36}$ erg s^{-1} (depending on the details of the assumed spectrum). Single-degenerate progenitor systems are thought to undergo a prolonged period ($\Delta t \approx 10^6$ years) of steady nuclear burning during the mass-transfer process. Such systems should appear as luminous X-ray sources: 10^{36}–10^{38} erg s^{-1} ($kT \approx 100$ eV). Indeed, nearly a hundred of these 'supersoft' sources have been identified so far in the Milky Way and other nearby galaxies, including M101 itself[20,21]. Double-degenerate

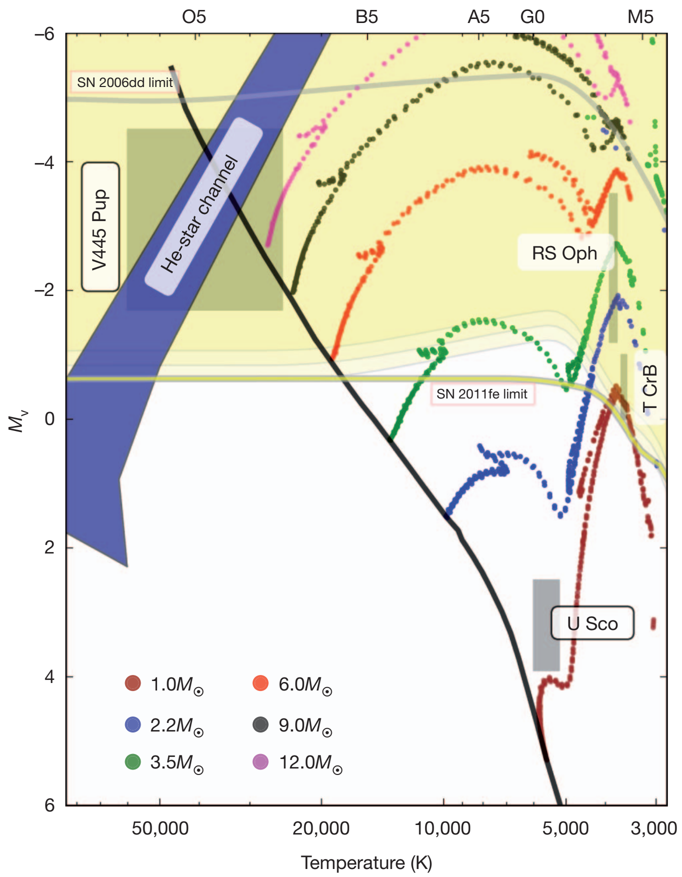

Figure 2 | Progenitor system constraints in a Hertzsprung–Russell diagram. The thick yellow line is the 2σ limit in M_V against effective temperature at the supernova location (see text) from a combination of the four Hubble Space Telescope filters, weighted using synthetic colours of redshifted stellar spectra at solar metallicity for that temperature and luminosity class. A more conservative limit comes from taking the single filter that most constrains the stellar type and luminosity class; shown is the 2σ limit assuming the adopted distance modulus[27,28] of 29.05 mag (middle grey curve at the bottom of the yellow shading) with a total uncertainty of 0.23 mag (top/bottom grey curve at the bottom of the yellow shading). We also show the theoretical estimates (He-star channel[13,14]) and observed candidate systems (V445 Pup[17], RS Oph[16], U Sco[18,29] and T CrB[16]). The grey-shaded rectangle shows the location of V445 Pup. Also plotted are the theoretical evolutionary tracks (from 1 Myr to 13 Gyr) of isolated stars for a range of masses for solar metallicity; note that the limits on the progenitor mass of SN 2011fe under the supersolar metallicity assumption are similar to those represented here. The grey curve at top is the limit inferred from Hubble Space Telescope analysis of SN 2006dd, representative of the other nearby type Ia supernova progenitor limits (see Supplementary Information). For the helium-star channel, bolometric luminosity corrections to the V band are adopted on the basis of effective temperature[30]. For an effective temperature of 3,000–4,000 K, as expected for the red-giant-branch stars, the M_V limit excludes progenitors brighter than an absolute I-band magnitude of $M_I \approx -2$. This limit is 2 mag fainter than the observed[28] tip of the red-giant branch in M101 and places an upper bound to the radius of $R \lesssim 60 R_\odot$ for an effective temperature of 3,500 K on any red-giant branch progenitor. In a progenitor model that requires RLOF, this limit then demands an orbital period smaller than 260 to 130 days in a binary system with a 1.3$M_\odot$ white dwarf (where the range of orbital period accommodates the 0.5$M_\odot$ − 2.5$M_\odot$ range allowed for a red-giant-branch star). The foreground Galactic and M101 extinction due to dust is negligible[7] and is taken to be $A_V = 0$ mag here. Had a source at the 2.0σ photometric level been detected in the Hubble Space Telescope images at the precise location of the supernova, we would have been able to rule out the null hypothesis of no significant progenitor with 95% confidence. We therefore use the 2σ photometric uncertainties in quoting the brightness limits on the progenitor system.

progenitor systems have also been predicted to emit X-rays[22,23], with X-ray luminosity of 10^{36}–10^{37} erg s^{-1}. Our historical X-ray limits are, unfortunately, not deep enough to rule out either channel.

We have also analysed pre-explosion mid-infrared data on M101 taken in 2004 with the Spitzer space telescope (see Supplementary Information). No point source was detected at the supernova location, to a mid-infrared luminosity of less than $(1–13) \times 10^{36}$ erg s^{-1}. These limits rule out bright red-giant mass donors for SN 2011fe in the symbiotic channel, but are consistent with a relatively faint secondary star in the RLOF channel. For a double-degenerate merger to produce a type Ia supernova, the merger product may need to evolve and cool slowly[24] for over a million years. This requires the radiated luminosity (mostly in the infrared) to be less than 4×10^{36} erg s^{-1}. The Spitzer nondetection limits are certainly consistent with the requirement of low-infrared luminosity for the double-degenerate models.

One test to determine whether SN 2011fe comes from the RLOF channel of the single-degenerate model, or from a double-degenerate merger, is to detect the surviving companion in the RLOF channel. But with our current resources, it would be very challenging to observe a subgiant mass donor, and nearly impossible to observe a main-sequence companion, unless there is excessive heating caused by the interaction between the companion star and the supernova ejecta.

Using historical imaging we have placed a limit on the progenitor of a type Ia supernova that is about a hundred times fainter than those previously achieved, showing that any evolved secondary star in the progenitor system of SN 2011fe must be less massive than $3.5M_{\odot}$. This rules out symbiotic progenitors like RS Oph and probably T CrB. These are fairly straightforward observational constraints, but in a companion paper[7] we use more indirect theoretical arguments to place additional limits. Expanding supernova ejecta should be shocked by contact with a large secondary[25], and the absence of this signature suggests that that secondary was not an evolved star. Furthermore, the ejecta could be shocked by debris that some studies[26] suggest should be present in a double-degenerate merger, although such shocked ejecta have not been seen. Taking all observational and theoretical limits together, the scenario of a white dwarf accreting from a main-sequence or subgiant companion is consistent with all constraints. Given the observed diversity of type Ia supernovae, however, the possibility of more than one progenitor channel for the class remains. As the trove of high-resolution wide-field imaging grows, covering more and more future supernova explosion sites, similar analyses may eventually resolve this possibility.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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