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Binary Paths to Type Ia Supernovae Explosions

Edited by

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COVER ILLUSTRATION: Supernova 2011fe in the Pinwheel Galaxy

SN 2011fe in the Pinwheel Galaxy (M101) at maximum brightness, a composite of optical data from the LCOGT 0.8m Byrne Observatory Telescope at the Sedgwick Reserve and hydrogen emission data (purple) from the *Palomar Transient Factory* (*PTF*). This Type Ia supernova was discovered about 44 days after the Symposium ended, and illustrates the promise and difficulties in discovering the nature of the progenitors.

At 6.4 Mpc, SN 2011fe was the closest Type Ia supernova in 25 years, and the capabilities of *PTF* allowed it to be discovered early, well before maximum brightness. It is perhaps the best-studied SN Ia. Deep observations across wavebands taken within days of explosion established that the exploding object was compact, and also placed constraints on both single-degenerate and double-degenerate progenitors. In addition, there are high-quality images at both x-ray and optical wavelengths taken prior to explosion.

Even with the unprecedented set of observational limits, a wide range of progenitor models are consistent with the data. Whatever the progenitor of SN 2011fe, other SNe Ia could have progenitors of other types.

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BINARY PATHS TO TYPE IA SUPERNOVAE EXPLOSIONS

PROCEEDINGS OF THE 281st SYMPOSIUM OF THE INTERNATIONAL ASTRONOMICAL UNION HELD IN PADOVA, ITALY JULY 4 - 8, 2011

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Summary

Preface

Three months after the end of this symposium, the Nobel prize for physics was awarded to three astrophysicists who inferred the existence of dark energy from Type Ia supernova data. Undoubtedly, it was a great year for scientists working on the mystery represented by Type Ia supernovae. The environment of IAU Symposium 281 resonated with energy and enthusiasm – the sessions were exciting and full of ideas.

More than 130 participants came from 30 different countries. The participants in IAUS 281 were diverse by any measure. Graduate students and post-doctoral fellows were a large fraction of the attendees. All of the participants brought enthusiasm and new ideas. The atmosphere was thus refreshing, charged with expectations and possibilities. Our aim was to bring together different communities: scientists working on supernovae, on close binary evolution, and on binary populations. A previous "SNova" semester-long program and conference were organized by Lars Bildsten, Rosanne Di Stefano, Bob Kirshner, and Craig Wheeler five years earlier at the Kavli Institute in Santa Barbara. Those of us who took part in either came home enriched and energized. One of our main aims was to rekindle the spirit of this previous experience, and in this we were successful.

There were many highlights at this Symposium. We will mention just a few that sparked lively discussion. Detailed simulations of Roche lobe overflow represent a new capability in which there was much interest. The possible detection of gravitational waves from close white dwarf binaries with space missions in future years is also very exciting. Population synthesis calculations in this new era of large surveys with unprecedented statistics are going to be more important than ever. The combination of theory and observations is powerful, and is leading us to consider a wider range of possible progenitor models than ever before.

The unexpected bonus of three eruptions of luminous recurrent novae within a little over two years before this Symposium, allowed new estimates of white dwarf masses and compositions. Interestingly, the possibility that many recurrent novae may host neon oxygen white dwarfs seems more likely now. Brand new spectra from the 10m South African Large Telescope (SALT) were presented in almost "real time". Optical spectroscopy appears also to be fundamental in probing the circumstellar environment in which SNe Ia explode, and several talks opened up new possibilities to search for the signature of single degenerate progenitors. In the meantime, radial velocity studies are paving an important avenue to search for double degenerates and improve their statistics.

We had several roundtable discussions, in which the observational results and theoretical predictions were carefully compared. This is what science is all about, constantly testing one's results and confronting them with others. Throughout the Symposium we experienced the tense and vibrating atmosphere that fosters intellectual and scientific development.

Many thanks to the "mystery speakers" selected without knowledge of the other participants to summarize the symposium at the end. Lilia Ferrario, Mukremin Kilic, and Alvio Renzini did an excellent job, focusing on "what we were taking home" from this conference. Lilia's contribution is included in these proceedings. Special thanks go of course to the participants who gave talks to the general public in Padova: Mario Livio, Lilia Ferrario, and Bob Williams. Their contributions were greatly appreciated by a large number of people in the community.

Finally, our sincere gratitude goes to all those who helped us offer an interesting and entertaining social program. We had two nice welcome parties, a classical music strings

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concert, a trip to Verona, a post-conference trip to Ferrara, and a wonderful dinner on the Colli Euganei. All LOC members were very helpful and kind. Special thanks to LOC co-chair Rossana Mareggini Strunce, and to Valeria Zanini, Stefano Ciroi and Valentina Cracco who were patient and present for the most difficult tasks and in the busiest moments. We were able to offer internships to support summer research projects by several students, thanks to funding from INAF and the City of Padova. Many thanks go to the Mayor of Padova, Flavio Zanonato (a keen supporter of Astronomy) and the city council of this lively town. In addition to the funding we received for the students' internships connected with the Symposium, we acknowledge with gratitude funding of the Department of Astronomy of the University for the string concert, financial help of the INAF-Padova Observatory, and the donation of very handy and practical structures to hold the posters, by ANEMOS, a private company specialized in metal shelves and structures.

Rosanne Di Stefano and Marina Orio, Septempber 2012

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Symposium Overview

Type Ia supernovae (SNe Ia) are bright, distinctive explosions that are effective tools to study the expansion history of the Universe. For decades they had been one of the key methods used to measure the current rate of expansion. Starting in the mid-1990s, new survey techniques were applied that increased the rate at which we discover SNe Ia and the distances out to which we can systematically probe. These new techniques allow astronomers to go beyond measurements of the rate of expansion, and to determine the acceleration as a function of cosmic time. We discovered that we live in what Robert Kirshner has called a “stop and go Universe”. The present-day acceleration is a clue to basic physics and its discovery has sparked research on dark energy and the cosmological constant. The 2011 Nobel Prize in Physics was awarded “for the discovery of the accelerating expansion of the Universe through observations of distant supernovae”.

Given the importance of Type Ia supernovae, it is remarkable that we still do not know the exact nature or natures of the astrophysical systems that generate them. The goal of IAUS 281 was to assess the state of searches for the progenitors and to make progress toward the solution of the so-called Type Ia progenitor puzzle. As we will describe below, the puzzle has many pieces. Furthermore, the physical processes associated with several crucial pieces of the puzzle are difficult to simulate, introducing significant uncertainties into the predictions.

We do know that Type Ia supernovae are exploding white dwarfs. We also know that, in order to explode, a white dwarf must gain mass. The progenitor puzzle is the problem of discovering how that happens. There are many models, almost all relying on the presence of a companion star that donates mass to the white dwarf. The models differ from each other in the mass of the companion star, its state of evolution, its orbital separation from the white dwarf at the time it begins to donate mass, the mass and state of the white dwarf, and the manner in which mass is transferred. Mass may be donated through winds or because the donor star fills its Roche lobe. The composition of the accreted matter and the amount of angular momentum it imparts to the white dwarf also vary among models. There may be many paths to explosion.

The rich panoply of models is often divided into two classes. Double-degenerate models are those in which the donor star is itself a white dwarf. The orbit is close and the less massive white dwarf is torn apart during a merger-like event. In single-degenerate models, the white dwarf gains matter more gradually, from a donor that is not degenerate. There are many possibilities within each class. A solution to the Type Ia progenitor puzzle would be a derivation, through theoretical and observational efforts, of the contribution of each possible channel in galaxies of different types and at different stages in the evolution of the Universe.

Achieving first-principles understanding for the SN Ia progenitor problem has proved difficult, because so many areas on the frontiers of astrophysics are involved. We need to understand the evolution of single stars, and both subtle and dramatic alterations introduced by evolution within an interacting binary. We need to understand the conditions under which white dwarfs gain mass or merge, the circumstances under which they explode, and the appearance of and effects of the explosion. This is far more complex than the already very challenging problem of the evolution and core-collapse explosion of massive single stars.

IAUS 281 took place during a time of great excitement, when new surveys, including the *Palomar Transient Factory (PTF)* and the *Panoramic Survey Telescope & Rapid Response System (Pan-STARRS)*, are discovering larger numbers of SNe Ia. Beyond that,

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data from many observing programs, complemented by a wide range of theoretical work, was calling into question some assumptions of long standing. During the Symposium we were able to consider these issues one by one, laying out the evidence on both sides.

We want to thank all of the authors represented in this volume. Your combined work paints a vivid picture of the state of the field, anticipating some of the progress made since the time of our meeting, and pointing the way to future work needed to resolve the Type Ia progenitor puzzle. The reader will find a diversity of opinions on a wide range of topics. We have not attempted to reconcile these differences, but have instead let the disagreements stand, because they reflect genuine physical uncertainties, many of which will need to be resolved before we can fully understand the nature of the progenitors. Those who attended the Symposium may notice that the order in which the papers appear does not exactly mirror the order in which the talks were given. The order we have chosen, described below, allowed us to maintain the coherence of the science themes while incorporating the papers on posters and minimizing changes that would otherwise be needed to account for presentations not written up for publication.

We started the Symposium and begin these proceedings in Part I with work on new surveys and the implications of the survey results for cosmology. A paper by Kirshner leads off, providing both the historical context and new results on observations of SNe Ia in the near infrared (NIR). Whereas at optical wavelengths, SNe Ia are "standardizable candles", their properties in the NIR are more uniform, making them more like "standard candles". The second presentation is an overview by Kasliwal of new work on transients, especially by *PTF*. Beyond the discovery of SNe Ia, *PTF* and other surveys discover many other transient phenomena that are linked to SNe Ia in direct and indirect ways through the physics of binary evolution. Some of these transients are of well-known types, such as novae, and others are yet-to-be-discovered, such as accretion induced collapse. Other interesting papers in this section discuss a variety of survey techniques as well as the properties and rates of SNe Ia in different stellar populations and as a function of redshift.

The papers in Part II set the stage for progenitor searches, reflecting several areas of astrophysics that must be well understood to derive the characteristics of the binaries within which SNe Ia occur. Section A of Part II focuses on the white dwarf: the range of masses and compositions expected for white dwarfs that are the end states of single stars or of stars in binaries. In addition, Rauch incorporates model atmospheres to derive synthetic spectra for hot white dwarfs. Section B of Part II is devoted to considering the importance of angular momentum transfer, which is expected to accompany mass transfer in at least some cases in which a white dwarf accretes matter at high rates. Although the physics needed to derive the evolution of realistic systems is difficult, and the physical conditions within which the evolution occurs are not yet well understood, the accretion of angular momentum has significant consequences. It can, for example, increase the critical mass needed for explosion, and can also introduce a wait time to explosion that alters the appearance and characteristics of the donor star both pre- and post-explosion. That this challenging theoretical work must be undertaken is illustrated by the discovery of remarkable high-mass spinning white dwarfs, like the "mystery object" discussed by Mereghetti and collaborators.

All models of the progenitors of SNe Ia involve epochs during which mass falls onto a white dwarf. The most common and best studied of accreting white dwarfs are those that accrete at the lowest rates: cataclysmic variables (CVs). In most CVs, the mass of the donor is so small that it could not possibly donate enough to the white dwarf to allow it to reach the Chandrasekhar mass, M_{Ch}. Furthermore, the rate of mass transfer is so low that much of the accreted matter may be lost during nova explosions. Nevertheless, CVs

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can provide insight into key elements of accretion onto white dwarfs. Both theoretical and observational studies of CVs and novae are included in Part III.

The rest of this volume is devoted to the full range of Type Ia supernova progenitor models. Because the goal of the work discussed in the Symposium was to discover which astrophysical systems become SNe Ia, the focus is on the binary models, which are the subject of Part IV.

It may seem obvious that the best way to discover the progenitors is to find them pre-explosion. This has been accomplished for core collapse supernovae, which can be detected from great distances because the stars that explode are very bright. Accreting white dwarfs can also be bright if the accretion rate is high. Not only is the accretion luminosity large, but nuclear burning of accreting matter can increase the luminosity by more than an order of magnitude. If the radiation from nuclear-burning white dwarfs should happen to emanate from a photosphere whose size is comparable to that of the white dwarf itself, then the progenitors could be observed as luminous supersoft x-ray sources (SSSs), with hundreds to about a thousand detectable in each of several nearby external galaxies. Yet typical observed populations of SSSs range from a handful in some early-type galaxies, to dozens in M101. We devoted a session to discussing the implications, which may be significant for both single-degenerate and double-degenerate models, and even for our general understanding of galactic populations of accreting white dwarfs, independent of the question of whether any of them ever explode. The papers in Section A of Part IV summarize key parts of this discussion, considering in what ranges of wavelengths the radiation from the white dwarf may be emitted, if not at x-ray wavelengths. Lepo discussed the possibility of enhanced UV emission, should the photosphere be somewhat larger. Nielsen and Kato discussed the effects of winds and possible emission at IR wavelengths. The question of what the progenitors look like is an important one, and the ideas put forward by the participants will certainly be pursued in future research.

In Section B of Part IV we turn to the somewhat lower accretion rates generally associated with recurrent novae. Anupama provides a comprehensive study of the recurrent nova phenomenon, which is the subject of observational and theoretical work described in most of the other papers in this section. Recurrent novae host white dwarfs with masses approaching M_{Ch}, accreting at moderate rates. The composition of the white dwarfs (carbon-oxygen versus oxygen-neon) and the question of whether, despite nova outbursts, they retain a large fraction of the accreted mass, are of prime interest to the SNe Ia community. The accreted mass can be provided by a close companion to the white dwarf, as in the U Sco system. It can also be provided by a giant, which may be donating mass because it fills its Roche lobe or else through winds. Systems with giant donors are referred to as symbiotics; present knowledge of symbiotics is summarized by Mikolajewska. Interestingly enough, as mentioned by Kirshner in this volume, PTF11kx has been reported to exhibit evidence that the progenitor was a symbiotic recurrent nova. Although additional research on this system is needed, the initial findings are intriguing. However, even should evidence for a symbiotic progenitor hold up, this doesn't mean that all SNe Ia have symbiotic progenitors. In fact, another SN Ia studied in detail in the months after the Symposium, SN2011fe, shown on the cover, is near enough to us that we can rule out the possibility that the donor was a giant during the years just prior to explosion.

The composition of the accreted material is also important. When the donor is a helium star or a helium white dwarf, matter falling toward the white dwarf will be helium rich, and the physics of steady nuclear burning and recurrent novae may be significantly different. The contributions from Wang & Han and Piersanti et al., which together comprise Section C of Part IV, are devoted to research on the helium donors to SNe Ia.

The papers in Section D of Part IV are devoted to ways in which we can search for double-white dwarf systems, some of which could merge in a Hubble time. Although the results so far are limited, calculations of the gravitational radiation expected from such systems, and the possibility of direct detection with LISA, formed the basis of exciting presentations. Developments since then may mean that the detection of gravity waves from space will be postponed, but the calculations may help to keep interest in this frontier field alive. Whatever the time scale for the detection of gravity waves from inspiraling white dwarfs, it is important to compute the double-white-dwarf merger rates, as presented by Toonen et al. in the final paper in this section.

The computation of rates is an important goal of the population synthesis studies, which are the subject of Section E of Part IV. Population synthesis is a method in which theoretical considerations are used to compute the evolution of a simulated population of binaries. For the progenitor problem, all evolutionary channels in which a white dwarf eventually achieves M_{Ch} are considered. Because the evolutions of individual binaries are computed, the time delay between star formation and explosion is known, and the distribution of delay times can be derived. This computed distribution can be compared with the distribution of delay times inferred from observations of SNe Ia in large numbers of early-type and late-type galaxies. Such comparisons have been used to assess the relative contributions of different channels, and especially to compare the roles of single-degenerate and double-degenerate binaries at early and late times. At the time of the Symposium a consensus had been building that double-degenerate binaries provide a larger signal at late times, in better agreement with observations, although the total rates were too low to agree with observations. The uncertainties are, however, large. The lead-off paper by Nelemans provides an important comparison of the results of different groups, and quantifies the differences which are simply manifestations of the uncertainties about the systems and processes involved in these rather difficult and complex calculations. Each of the six other talks included in Section E of Part IV represent state-of-the art population synthesis results. The papers, and especially the discussion that occurred during the sessions in which they were presented, show how some of the disagreements can potentially be resolved. These sessions were fascinating and productive, generating ideas for future collaborative efforts.

In Part V the discussion moves on to the relationship between the progenitor models and the explosions, as well as the signatures both during and afterward that might provide clues to the nature or natures of the progenitors. For many years, single-degenerate progenitors have been favored, partly because calculations of the results of white-dwarf/white-dwarf mergers did not seem to produce explosions with the characteristics of SNe Ia. Newer calculations, including those presented at the Symposium, provide hints that there may be a relevant part of the parameter space where white-dwarf/white-dwarf mergers can produce SNe Ia explosions. Even more tantalizing is the possibility that sub-Chandrasekhar mergers of white dwarfs may lead to normal SNe Ia explosions, especially considering these mergers are expected to occur more frequently than their Chandrasekhar-mass counterparts. Papers on these calculations form a significant part of Section A of Part V, in which some work on explosions in single-degenerate systems is also presented.

Classic observational studies have used light curves and spectra to transform SNe Ia into standardizable candles. The papers in Section B of Part V focus on the clues to the nature of the progenitors that may be derived from the form of the light curve or from post-explosion spectra. In many single-degenerate models, some of the donor's mass is ejected from the binary during the epoch when the white dwarf is accreting matter at high rates. Signs of interaction between the supernova and circumbinary material have mostly proved elusive, however. Important progress along these lines is reported by both Patat and Sternberg. Livio suggests that signatures of polarization potentially detectable in future observations may be able to distinguish between single-degenerate and double-degenerate progenitors. A range of observational tests are explored in the seven papers that comprise this section.

Finally, the search for clues to SNe Ia progenitors in and near supernova remnants is the subject of the papers in Section C of Part V. In single-degenerate models the exploding white dwarf must have a non-degenerate companion during the interval in which it gains mass. This companion should survive the explosion. Through the years there have been several searches for companion stars. Ruiz-Lapuente and collaborators update their influential work in which they identified a specific star as the potential widowed donor of Tycho's supernova, SN 1572. They also report upper limits for the donor star in SN1006. Kerzendorf considers the same remnants, and reports somewhat different results. Pagnotta & Schaefer report on the search for a donor star in the remnant of a supernova in the LMC. Beyond the direct detection of the donor, characteristics of the supernova remnant provide clues to the nature of the progenitor. Chiotellis et al. report on evidence that both the Kepler and Tycho supernovae interacted with circumbinary material, perhaps supporting a single-degenerate origin, while Usuda et al. have applied the innovative technique of light echoes to determine the supernova type.

The article by Ferrario is her summary of the results presented in the Symposium and the discussions they sparked. The bottom line is that the debate as to the nature or natures of the progenitors continues, with no one model clearly preferred on all counts or for all SNe Ia.

Looking back on the Symposium, it is encouraging that the focus of so much of the reported research was on ways to find positive evidence of the nature of the progenitors. The increasing sensitivity of observations is making it more likely that discoveries can be made and that, if limits are placed, they are meaningful. At the same time, the present generation of surveys is discovering more SNe Ia at earlier times. On the theoretical front, it is also a new world, in which we are confronting the difficult problems, from hydrodynamical simulations of the progenitor binaries to the role played by angular momentum, to make new types of predictions. Although the Type Ia progenitor puzzle is one of long standing, the work presented at IAU Symposium 281 provides hope that we will come to understand the natures of the progenitors, perhaps even within the next decade.

Rosanne Di Stefano, Marina Orio, and Maxwell Moe, editors
Cambridge, MA, September 2012

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