WILHELM UND ELSE HERAEUS-STIFTUNG

660. WE-Heraeus-Seminar

Supernovae - From Simulations to Observations and Nucleosynthetic Fingerprints

January 21 - 24, 2018
Physikzentrum Bad Honnef/Germany

Introduction

The Wilhelm and Else Heraeus Foundation (Wilhelm und Else Heraeus-Stiftung) is a private foundation which supports research and education in science, especially in physics. A major activity is the organization of seminars. To German physicists the foundation is recognized as the most important private funding institution in their fields. Some activities of the foundation are carried out in cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft).

Scope of the 660. WE-Heraeus-Seminar:

Observations and theoretical models have made impressive progress in understanding supernova explosions from massive stars and white dwarfs thanks to the advent of huge transient surveys and advances in high-performance computing. To consolidate progress, it is important to make specialists in different aspects of supernova research aware of progress and challenges on other fronts. This seminar will bring together world-leading experts, early career researchers, and students to discuss the physical modelling of stellar explosions, their nucleosynthesis, radiation transfer, and supernova observations to further our understanding of these dramatic events that are crucial for the chemical enrichment of the Universe.

Key science topics

- What are the explosion mechanisms of SNe? Which CCSNe are neutrino-driven, and for which ones do we need some kind of magneto-rotational mechanism? How are black holes formed and what is the SN-GRB connection? Are thermonuclear explosions dominated by deflagration or detonation burning? Do they explode near or below the Chandrasekhar-mass limit of CO WDs? 3D effects are critical to make progress on these questions, and the workshop will have a strong focus on the latest 3D models.
- What nucleosynthesis do SNe produce? SNe are believed to be the main factories of all heavy elements in the Universe, but little quantitative results yet exist on this process. How well do we understand the origin of different elements, from comparison of nucleosynthesis models and spectral analysis? What does the production of different elements tell us about the progenitor and explosion properties?
- What do current models for light curves and spectra of SNe tell us? The critical link between explosion models and observations is the radiative transfer modelling of light curves and spectra. What properties can we robustly infer with modern codes, and what properties are still difficult to pin down due to limitations in the physical modelling? How do these limitations affect our search for the progenitors of SNe? Can we constrain the most fundamental parameter of the progenitors: the mass of the exploding star?
- What new observational data are needed to make the next breakthroughs? It is at the interface between forefront theory and observations that progress is made. What are the current theoretical predictions that are most valuable to test observationally, in particular in the context of the 'zoo' of transients discovered in the past decade?

Program

Program

Sunday, January 21, 2017

17:00 – 21:00	Registration	
18:30	*BUFFET SUPPER / Informal get together*	
20:00 – 21:00	Scientific organizers	**Opening and welcome Kick-off presentation**

Monday, January 22, 2017

07:30	BREAKFAST	
08:45 – 09:30	Friedrich Röpke	**Simulations of thermonuclear explosions in white dwarf stars**
09:30 – 09:45	Shing-Chi Leung	**Understanding Type Ia supernova explosion mechanisms by its nucleosynthesis yield**
09:45 – 10:00	Sabrina Gronow	**Sub-Chandrasekhar mass white dwarfs as Type Ia supernova progenitors**
10:00 – 10:15	Barnabás Barna	**Abundance tomography of Type Iax Sne**
10:15 – 10:45	*COFFEE BREAK*	
10:45 – 11:30	Hans-Thomas Janka	**3D core-collapse supernova modeling and applications to Cas A and other supernova remnants**
11:30 – 11:45	David Vartanyan	**Opacities and rotation in the revival of the fittest**
11:45 – 12:00	Takami Kuroda	**Core collapse of massive stars(11.2-70Msun) and black-hole formation with 3DGR spectral neutrino transport**

Program

Monday, January 22, 2017

12:00 – 12:15	Jérôme Guilet	**How to form a millisecond magnetar? Magnetic field amplification in a protoneutron star**
12:15 – 12:30	Michael Gabler	**Young supernova remnants in long-time, 3D supernova simulations**
12:30	**Conference Photo** (in the foyer of the lecture hall)	
12:35	*LUNCH*	
14:00 – 14:45	Martin Obergaulinger	**Core collapse with rotation and magnetic fields**
14:45 – 15:30	**Poster flash presentations I** (3 min. / 1 slide each)	
15:30 – 16:00	COFFEE BREAK	
16:00 – 16:45	Ivo Seitenzahl	**Nucleosynthetic fingerprints of thermonuclear supernova models**
16:45 – 17:30	Claudia Travaglio	**Multi-d core collapse supernovae and nucleosynthesis**
17:30 – 17:45	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
17:45 – 18:30	**Poster session I**	
19:00	*HERAEUS DINNER* *(cold & warm buffet, free beverages)*	

Program

Tuesday, January 23, 2017

07:30	*BREAKFAST*	
08:45 – 09:30	Almudena Arcones	**Nucleosynthesis in CCSNe**
09:30 – 09:45	William Raphael Hix	**Lessons on supernova nucleosynthesis from multi-dimensional models**
09:45 – 10:00	Carla Fröhlich	**CCSN nucleosynthesis yields across the mass range**
10:00 – 10:15	Alexander Heger	**Nucleosynthesis in the first supernovae**
10:15 – 10:45	*COFFEE BREAK*	
10:45 – 11:00	Roland Diehl	**Gamma-ray measurements from supernovae and their radioactive afterglows**
11:00 – 11:45	Paolo Mazzali	**Supernova spectral modelling**
11:45 – 12:00	Nahliel Wygoda	**The physical width-luminosity relation(s) for Type Ia supernovae favour sub-Chandrasekhar and collision models**
12:00 – 12:15	Mattia Bulla	**Polarization as a test for multi-dimensional explosion models of Type Ia supernovae**
12:15 – 12:30	Tamar Faran	**Recombination Effects on Supernova Light-Curves**
12:30	*LUNCH*	

Program

Tuesday, January 23, 2017

14:00 – 14:45	Sergei Blinnikov	**Central Engines of superluminous supernovae and their environment**
14:45 – 15:30	**Poster flash presentations II** (3 min. / 1 slide each)	
15:30 – 16:00	COFFEE BREAK	
16:00 – 16:45	D. John Hillier	**Spectral synthesis modelling with CMFGEN**
16:45 – 17:00	Alexey Tolstov	**Supernovae from 8-12 solar mass stars : Multicolor light curve simulations**
17:00 – 17:15	Mattias Ergon	**Modelling the spectral evolution of supernovae**
17:15 – 17:30	Alexandra Kozyreva	**The variety of pair-instability supenovae**
17:30 – 18:15	**Poster session II**	
18:15 – 18:30	**Poster award cermony**	
19:00	*DINNER*	

Program

Wednesday, January 24, 2017

07:30	*BREAKFAST*	
08:30 – 09:15	Kate Maguire	**Observational constraints on the explosion mechanisms of Type Ia supernovae**
09:15 – 10:00	Maryam Modjaz	**The spectroscopic connection between superluminous SNe and SN-GRBs**
10:00 – 10:30	*COFFEE BREAK*	
10:30 – 10:45	Jakob Nordin	**Supernova physics from spectrophotometric data**
10:45 – 11:00	Subhash Bose	**Multi-band observations of the closest Type I superluminious supernova 2017egm/Gaia17biu in a "normal" metal rich spiral galaxy**
11:00 – 11:15	Brad Tucker	**High-cadence light-curves with Kepler, TESS, and GLUV**
11:15 – 12:00	Jesper Sollerman	**ZTF and supernovae from PTF**
12:00	*LUNCH*	
13:30 – 14:00	Claes Fransson	**Summary talk**
14:00 – 14:15	Scientific organizers	**Final discussion and closing remarks**

End of the seminar *and FAREWELL COFFEE* ***/ Departure***

Please note that there will be ***no*** *dinner at the Physikzentrum on Wednesday evening for participants leaving the next morning.*

Posters

POSTERS

1.	Erica Bloor	**Characterizing the most important instabilities in core-collapse supernovae**
2.	Alexey Bobrick	**Mass transfer in white dwarf-neutron star binaries**
3.	Emma Callis	**Photometric and spectroscopic study of the interacting Ibn supernova SN2015G**
4.	Ting-Wan Chen	**How to find young superluminous supernovae with GREAT survey**
5.	Aleksandar Cikota	**Investigating progenitors of Type Ia supernovae using spectropolarimetry**
6.	Peter Clark	**The unusual interacting supernova LSQ13ddu**
7.	Mariangelly Díaz-Rodríguez	**Progenitor mass distribution for core-collapse supernova remnants in M31 & M33**
8.	Andreas Flörs	**Limits on stable iron in Type Ia supernovae from late-time IR spectroscopy**
9.	Thierry Foglizzo	**New insights on the development of asymmetries during the collapse of a rotating star**
10.	Dan Gay	**Modelling of low-mass core-collapse supernovae spectra and lightcurves**
11.	Tomoyasu Hayakawa	**A collapsar model with disk wind: Implications for supernovae associated with gamma-ray bursts**
12.	Rubina Kotak	**On the peculiar late-time properties of a low-luminosity type II-plateau supernova**
13.	Florian Lach	**Two- and three-dimensional simulations of Type Ia supernovae: Chandrasekhar mass deflagrations**
14.	Naveh Levanon	**Early UV emission from disc-originated matter (DOM) in Type Ia supernovae in the double-degenerate scenario**

POSTERS

15.	Joe Lyman	**The environments of supernovae Iax as an insight on their progenitor systems**
16.	Mark Magee	**Modelling the early time behaviour of Type Ia supernovae: Effects of the ^{56}Ni distribution**
17.	Andrea Nagy	**Early- and late-time light curve modelling of stripped-envelope supernovae**
18.	Marat Potashov	**Some problems in spectral modelling of pulsational pair instability SN 2006gy**
19.	Nir Sapir	**Double-peaked SN light curves may be explained by luminosity suppression in standard polytropic envelopes**
20.	Fabian Schneider	**Influence of binary mass-transfer on pre-supernova stellar structures**
21.	Luke Shingles	**Late-phase radiative transfer of Type Ia supernovae**
22.	Ása Skúladóttir	**Zinc in the sculptor dwarf spheroidal galaxy**
23.	Georg Stockinger	**3D simulations of low-mass core-collapse supernovae: Connecting shock-revival and remnant phase**
24.	Tamas Szalai	**A comprehensive analysis of *Spitzer* supernovae**
25.	Stefan Taubenberger	**Insights from late-time observations of SN 2012dn**
26.	Christian Vogl	**EPM dilution factors revisited**
27.	Naveen Yadav	**On the properties of convection in the Si-O layers of a massive star prior to collapse**

Abstracts of Lectures

(in chronological order)

Simulations of thermonuclear explosions in white dwarf stars

F. K. Röpke

Institut für Theoretische Astrophysik, Zentrum für Astronomie der Universität
Heidelbreg, Heidelberg, Germany
and
Heidelberger Institut für Theoretische Studien, Heidelberg, Germany
E-mail: friedrich.roepke@h-its.org

Type Ia supernovae are among the most prominent cosmic explosions in the current universe. Because of their extreme brightness and correlations between observable properties that allow for a calibration as distance indicators, they have been instrumental in surveying its geometry. At the same time, these explosions are prolific sources of iron group elements and shape the chemical structure of their host galaxies. Despite their significance for various astrophysical processes, the mechanism of Type Ia supernovae remains enigmatic. A fundamental handicap for model building is the unknown nature of the progenitor system. Several distinct scenarios are currently discussed involving explosions of Chandrasekhar-mass and sub-Chandrasekhar mass white dwarf stars. These can be tested in numerical simulations, provided that uncertainties in the physical explosion mechanism and numerical approximations can be controlled. This is a very challenging task because of the pronounced multi-scale multi-physics character of the explosion process. Nonetheless, significant progress was possible with multidimensional hydrodynamic explosion simulations, that provide the basis for the prediction of observables. I will review the involved challenges, describe possible approaches to model building and numerical implementation, and give examples for simulations of thermonuclear supernova explosions in different scenarios. Finally, I will discuss achievements and shortcomings of current multidimensional models and outline paths to validate them based on comparison with various observational data.

Understanding Type Ia supernova explosion mechanisms by its nucleosynthesis yield

S.-C. Leung[1] and **K. Nomoto**[1]

[1]Kavli Institute for the Physics and Mathematics of the Universe, The University of Tokyo, Chiba, Japan
E-mail: shingchi.leung@ipmu.jp

Recent Type Ia supernova (SN Ia) observations have demonstrated that its explosion has more variations than what is expected in the theory. In order to match with the observed diversity, survey of SN Ia explosion models with a much wider parameter space becomes necessary. In this talk, I will report the parameter survey of nucleosynthesis yield [1] from the arrays of SN Ia models based on the multi-dimensional simulations of Chandrasekhar and sub-Chandrasekhar mass white dwarf explosions. Then, I will demonstrate how the explosion mechanism and their progenitors of the observed SN Ia can be systematically revealed. Some well observed supernovae and remnants are used as examples.

First, I will demonstrate how to use the iron-peak elements Mn, Fe and Ni as the clues to recover the SN Ia progenitor. Using the light curves and spectra of some well observed SN Ia (e.g. SN 2011fe and SN 2012cg) and SN remnant (e.g. 3C 397), I constrain their corresponding progenitors. I will focus on how their progenitor white dwarf mass and metallicity can be obtained.

Second, I will reexamine the explosion mechanism of SN 2014J. This supernova is special because of its early Ni-56 signals and non-monotonic variations of Co-56 line strength in time. I will present how such features of this SN can be naturally realized by the multi-dimensional explosion simulations of a sub-Chandrasekhar mass white dwarf.

References

[1] Shing-Chi Leung and Ken'ichi Nomoto, accepted for publication in ApJS, arXiv: 1710.04254 (2017)

Sub-Chandrasekhar mass white dwarfs as type Ia supernova progenitors

S. Gronow[1,2]

[1] Heidelberger Institut für Theoretische Studien, Schloss-Wolfsbrunnenweg 35,
69118 Heidelberg, Germany
[2] Zentrum für Astronomie der Universität Heidelberg, Astronomisches Recheninstitut,
Mönchhofstr. 12-14, 69120 Heidelberg, Germany
E-mail: sabrina.gronow@h-its.org

Supernovae are the main contributers of iron in our galaxy and influence the galactic chemical evolution. The moving mesh code AREPO [1] is used to simulate the double detonation of a sub-Chandrasekhar mass white dwarf as a possible progenitor of a type Ia supernova. It allows a parallel treatment of the occurring hydrodynamics and a nuclear network. The white dwarf is set up to consist of a carbon and oxygen core with a helium shell. Different initial models are analyzed for their evolution and final abundances in three dimensional simulations. A new explosion mechanism is found which allows a comparison with previous results (see for example [2] and [3]).

References

[1] V. Springel, Monthly Notices of the Royal Astronomical Society 401, 791–851 (2010)
[2] M. Fink, et al., Astronomy & Astrophysics 514, A53 (2010)
[3] S. A. Sim, et al., Monthly Notices of the Royal Astronomical Society 420, 3003-3016 (2012)

Abundance tomography of Type Iax SNe

B. Barna[1,2], T. Szalai[2], W. Kerzendorf[1]
[1]ESO, Garching bei München, Germany
[2] University of Szeged, Szeged, Hungary
E-mail: bbarna@eso.org

Despite the decade-long, intensive study, the origin of the different subclasses of thermonuclear supernovae has remained an open question. Although there are promising explosion scenarios for explaining the observational attributes of these objects, the calculated chemical structures vary on a wide scale. Constraining the chemical abundances in the supernova atmosphere could allow a powerful tool to test the different theories.

Using the method of abundance tomography, we define a multi-layer synthetic atmosphere, where the fractions of the chemical elements are fitting parameters in each velocity shell. The modeling of the supernova spectra obtained at different epochs scans through the optically thin region of the atmosphere and provides the abundance distribution of the ejecta.

Only a few studies based on abundance tomography were published in the last decade; however, Type Iax SNe were not the subject of this kind of analysis until now. The members of this subclass are peculiar thermonuclear explosions showing relatively low peak absolute brightness and low expansion velocities. Because of the wide range of physical properties, SNe Iax offer excellent possibilities to test different explosion scenarios. However, the high number of overlapping spectral features appearing even at early epochs challenges the abundance tomography technique.

We present the first results on abundance tomography of Type Iax SNe carried out using the radiative transfer code TARDIS. We discuss the assumed physical properties and the used fitting process regarding this peculiar class of supernovae. Finally, a possible correlation between the physical parameters and the abundance distribution is shown, together with an outlook on the possible progenitor scenarios.

3D core-collapse supernova modeling and applications to Cas A and other supernova remnants

Hans-Thomas Janka

Max Planck Institute for Astrophysics, Garching, Germany
E-mail: thj@mpa-garching.mpg.de

First three-dimensional, first-principle simulations of core-collapse supernovae have become possible in the recent past. They demonstrate the basic viability of the neutrino-driven mechanism for powering the explosions of the majority of supernova progenitors. Although a number of open questions remain to be settled, the explosion models are now sufficiently mature to strive for detailed comparisons against observations, for example considering well studied, nearby supernovae and young supernova remnants. This talk will review our basic understanding of the explosion mechanism and report some results of such observational tests.

References

[1] F.J. Abellán, et al., ApJL **842**, L24 (2017)
[2] H.-T. Janka, et al., ARNPS **66**, 341 (2016)
[3] S. Katsuda, et al., arXiv:1710.10372; ApJ submitted
[4] T. Melson, et al., ApJL **801**, L24 (2015)
[5] T. Melson, et al., ApJL **808**, L42 (2015)
[6] B. Müller, et al., MNRAS **472**, 491 (2017)
[7] A. Summa, et al., arXiv:1708.04154; ApJ in press
[8] V. Utrobin, et al., A&A **581**, A40 (2015)
[9] A. Wongwathanarat, et al., ApJ **842**, 13 (2017)

Opacities and Rotation in the Revival of the Fittest

Vartanyan, David and **Burrows, Adam**

[1]*Princeton U, Princeton, NJ,*
[2]*Princeton U, Princeton, NJ, USA*
E-mail: dvartany@princeton.edu

For over five decades, the mechanism of explosion in core-collapse supernovae has been a central unsolved problem in astrophysics, challenging both our computational capabilities and our understanding of relevant physics. Current simulations often produce explosions, but they are at times under-energetic. The neutrino mechanism, wherein a fraction of emitted neutrinos is absorbed in the mantle of the star to reignite the stalled shock, remains the dominant model for reviving explosions in massive stars undergoing core collapse. We present here a diverse suite of 2D axisymmetric simulations produced by FORNAX, a highly parallelizable multidimensional supernova simulation code. We explore the effects of various corrections, including the many-body correction, to neutrino-matter opacities and the possible role of rotation in promoting explosion amongst various core-collapse progenitors. We find a sensitively crucial dependence on critical conditions distinguishing an explosion from a dud.

References

[1] Vartanyan, David. 2017ab, (in prep.)
[2] Burrows, Adam, Vartanyan, David, et. al. Space Science Reviews (accepted).

Core collapse of massive stars(11.2-70Msun) and black-hole formation with 3DGR spectral neutrino transport

T. Kuroda[1], K. Kotake[2], T. Takiwaki[3] and F.-K. Thielemann[4]

[1]Institute für Kernphysik, Technische Universität Darmstadt,
Schlossgartenstrasse 9, Darmstadt, Germany
[2] Department of Applied Physics, Fukuoka University,
8-19-1, Jonan, Nanakuma, Fukuoka, Japan
[3]Division of Theoretical Astronomy, National Astronomical Observatory of Japan,
2-21-1, Osawa, Mitaka,Tokyo, Japan
[4]Department of Physics, University of Basel, Klingelbergstrasse 82, Switzerland
E-mail: takami.kuroda@physik.tu-darmstadt.de

We report our recent study on the final fate of non-rotating massive stars with four different masses of 11.2, 15, 40, and 70 $M_\odot$. By using a 3DGR spectral neutrino transport code, we follow up to ~500 ms after bounce and find a various post bounce evolutions. In the lightest progenitor model (11.2$M_\odot$), the largest shock radii are seen and it eventually turns into the explosion phase. While in the middle progenitor mass models (15 and 40 $M_\odot$), there is no indication of the shock revival during our simulation time. The most massive star (70$M_\odot$) also shows a rapid shock expansion at ~300ms after bounce due to violent convection motion behind the shock. The convection motion is triggered by enormous of neutrinos emerged from the central extremely hot unshocked core (~170MeV). The shock expansion, however, is immediately followed by a second collapse of the proto-neutron star (PNS) and a black-hole (BH) formation. We estimate the BH property and find that its baryonic(gravitational) mass is ~2.6(2.5) $M_\odot$. By comparing with a previous 1D study which uses similar setups, we find that those BH properties are consistent. Since our most massive progenitor model possesses CO core with ~33$M_\odot$, it might lead to a ~33$M_\odot$ BH albeit depending on the binary evolution. Our result thus suggests the importance of long term calculation beyond the BH formation to indicate a possible scenario for the origin of stellar mass binary BHs such as of GW150914. In this talk, we also mention gravitational wave and neutrino signals to discuss multi messenger astronomy.

How to form a millisecond magnetar? Magnetic field amplification in a protoneutron star

J. Guilet[1]

[1]CEA Saclay/Department of Astrophysics, Gif-sur-Yvette, France
E-mail: Jerome.guilet@cea.fr

Extremely strong magnetic fields of the order of 10^15 Gauss are required to explain the properties of magnetars, the most magnetic neutron stars. Such a strong magnetic field is expected to play an important role for the dynamics of core-collapse supernovae, and in the presence of rapid rotation may power superluminous supernovae and hypernovae associated to long gamma-ray bursts. The origin of these strong magnetic fields remains, however, obscure and most likely requires an amplification over many orders of magnitude in the protoneutron star. One of the most promising agents is the magneto-rotational instability (MRI), which can in principle amplify exponentially a weak initial magnetic field to a dynamically relevant strength. I will describe our current understanding of the MRI in protoneutron stars and show recent results on the impact of physical conditions specific to protoneutron stars such as neutrino radiation, strong buoyancy effects and large magnetic Prandtl number.

Young supernova remnants in long-time, 3D supernova simulations

M.Gabler, H-Th. Janka and A.Wongwathanarat

MPI for Astrophysics, Garching, Germany
E-mail: miga@mpa-garching.mpg.de

Recent years have brought a tremendous progress in the modelling of self-consistent neutrino driven supernova (SN) explosions. Not only that the first 3D simulations have become accessible and have shown successful explosions, also first long-term simulations up to the SN breakout from the progenitor have been performed with realistic initial conditions. These studies allowed to investigate the development of hydrodynamical instabilities during the expansion of the ejecta. Also the observations with 3D information about the structures of different elements and molecules in young and nearby supernova remnants (SNR) have reached a state at which they can be compared to 3D long-time simulations. However, to challenge these models with observations is not easy. It can be straight forward, e.g. when comparing abundances of radioactive elements to the simulations, but can be a major problem when we want to study e.g. emission lines of molecules which in the first place have to be formed and second have to be excited. In ordinary SNR the ejecta structures are determined by the explosion engine, the instabilities during the propagation through the progenitor, the interaction with various shocks and the ISM. We present recent long-time, 3D simulations of core-collapse supernovae and compare them to particular supernova remnants and discuss what we can learn from this comparison.

Core collapse with rotation and magnetic fields

M. Obergaulinger[1] **and M.Á. Aloy**[1]

[1]*Departament d'Astroniomia i Astrofísica, Universitat de València, València, Spain*
E-mail: martin.obergaulinger@uv.es

Rapidly rotating stars that produce high-mass proto-neutron stars are considered potential progenitors of gamma-ray bursts that might be powered by a collapsar, i.e., a black hole surrounded by an accretion torus, or, if collapse to a black hole does not occur sufficiently early, by a long-lived proto-magnetar. Coupling special relativistic MHD, a pseudo-relativistic gravitational potential, and two-moment neutrino transport, we performed axisymmetric simulations of stars of 35 solar masses that fall into the class of potential GRB progenitors [1]. The results show explosions launched by mechanisms to which neutrino heating, rotation, and magnetic fields contribute to different degrees. The explosions occur in parallel to ongoing accretion onto the PNS, hence allowing for its growth in mass and rotational energy and, as a possible consequence, for later GRBs.

References

[1] M. Obergaulinger, M.Á. Aloy, MNRAS **469**, L43-L47 (2017)

Nucleosynthetic Fingerprints of Thermonuclear Supernova Models

I. R. Seitenzahl[1]

[1] *School of Physical, Environmental and Mathematical Sciences,*
The University of New South Wales,
Australian Defence Force Academy,
Canberra, ACT, 2600, Australia
E-mail: i.seitenzahl@adfa.edu.au

In 2011 the Nobel Prize in Physics was awarded for using Type Ia supernovae (SNe Ia) to demonstrate the accelerated expansion of the Universe. Despite the importance of this result, the debate about the nature of the progenitors of SNe Ia remains unsettled. Several viable progenitor systems and explosion mechanisms have been proposed. However, although many of these models can be successfully exploded on supercomputers, a comprehensive understanding of the different paths to explosion is still lacking. This „SN Ia progenitor and explosion mechanism problem“ is one of the great, unsolved problems in astrophysics, complicated by the fact that in recent years several unique sub-classes of SNe Ia have been described. I will discuss leading explosion models for SNe Ia, present results from multi-dimensional hydrodynamical simulations of the final seconds of the star's life, and highlight our quest to predict testable observables for the different suggested progenitor and explosion mechanisms. I will emphasize the different nucleosynthetic signatures of select classes of SN Ia explosions, discussing fingerprints of the nucleosynthesis in optical spectra, late-time light curves, and chemical evolution.

References

[1] I. R. Seitenzahl & D. M. Townsley, Handbook of Supernovae (2017)
[2] I. R. Seitenzahl et al., A&A Letters, **559**, 5 (2013)
[3] I. R. Seitenzahl et al., MNRAS, **429,** 1156 (2013)
[4] I. R. Seitenzahl, S. Taubenberger & S. A. Sim, MNRAS, **400,** 531 (2009)

Multi-d core collapse supernovae and nucleosynthesis

Travaglio C. *(INAF-Turin, Italy, E-mail: travaglio@oato.inaf.it)*
Wongwathanarat A. *(MPA-Garching bei Muenchen, Germany)*
Janka H.-T. *(MPA-Garching bei Muenchen, Germany)*

The explosion of massive stars as core-collapse supernovae represents one of the outstanding problems in modern astrophysics. Core-collapse supernovae figure prominently in the chemical evolution of galaxies as the dominant producers of elements between oxygen and the iron group, and they play an important role in the production of elements heavier than Fe. They represent a key ingredient in understanding the history of chemical enrichment of the Universe.

We present in this work a detailed analysis of nucleosynthesis calculations of a 15 $M_{\odot}$ neutrino-driven supernova explosions in 3D (explosions, approximative neutrino treatment, progenitors are presented by Wongwathanarat et al. 2015). Nucleosynthesis calculations are performed in a post-process using tracer particles method (TONiC code, Travaglio et al. 2011). The nucleosynthesis network used is based on 1500 isotopes, and for the first time about 500.000 tracer particles cover the star up to the explosive C-burning shell. We also discuss a the consequences for using different nuclear reaction networks (Basel 2009 as well as JINA 2012). The nuclear processes included are electron captures, neutron captures, alpha captures and photodisintegrations.

A detailed comparison of the nucleosynthesis calculation between 3D and 1D models (where also the 1D model includes neutrino-driven explosion) will be presented providing interesting information on

1. overproduction of neutron-rich material
2. elemental and isotopic abundances information of elements like Mn, Cr, Sc, Cu & Zn to better understand the observations in metal-poor stars in our Galaxy as well as in external objects
3. radiogenic material
4. potential source of p-process nuclei.

Nucleosynthesis in CCSNe

A. Arcones[1,2], **J. Bliss**[1], **M. Reichert**[1]
[1]Institute für Kernphysik, TU Darmstadt, Germany
[2] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
E-mail: almudena.arcones@physik.tu-darmstadt.de

Core-collapse supernovae produce iron group elements during the explosion as well as elements up to Silver in the neutrino-driven ejecta. We have performed a systematic study of the nucleosynthesis in neutron-rich ejecta. The astrophysical uncertainties are analyzed based on a steady-state wind model [1]. We have found that the nucleosynthesis can be classified into four characteristic abundance patterns. Moreover, we have carried out an extensive Monte Carlo study and identify the most critical (alpha,n) reactions [2]. Combining astrophysics and nuclear physics uncertainties, one can use observations to constrain and understand core-collapse supernovae. In order to have a successful r-process and to produce the heaviest elements in core-collapse supernovae, magnetic fields are necessary. We will report the impact of rotation and magnetic fields based on recent simulations including detailed neutrino transport [3].

References

[1] J. Bliss et al., in prep.
[2] J. Bliss et al., J. Phys. G **44**, 054003 (2017), J. Bliss et al. in prep.
[3] M. Obergaulinger & M.A. Aloy, MNRAS **469**, L43 (2017).

Lessons on Supernova Nucleosynthesis from Multi-Dimensional models

W. R. Hix[1] **and J. A. Harris**[2]
[1]Physics Division, Oak Ridge National Laboratory, Oak Ridge TN 37831, USA
[2]National Center for Computational Sciences, Oak Ridge National Laboratory, Oak Ridge TN 37831, USA
E-mail: raph@ornl.gov

As we enter the era where multi-dimensional models for core collapse supernovae (CCSN) including sophisticated neutrino transport can be continued to the time when nucleosynthesis is complete, we are uncovering a number of new features and misconceptions in our understanding of CCSN nucleosynthesis. I will discuss the insights into supernova nucleosynthesis we are gleaning from our models using the CHIMERA code, including nucleosynthesis processes not considered in conventional bomb or piston models for CCSN nucleosynthesis.

CCSN nucleosynthesis yields across the mass range

C. Fröhlich[1] , S. Curtis[1] and K. Ebinger[2,1]

[1] *Department of Physics, North Carolina State University, Raleigh NC, USA*
[2] *GSI Helmholtzzentrum fuer Schwerionenforschung, Darmstadt, Germany*
E-mail: cfrohli@ncsu.edu

We established a parameterized, spherically symmetric explosion method (PUSH) that is able to reproduce the observational properties of SN 1987A [1]. Using this method, we have performed systematic explodability [2] and nucleosynthesis [3] studies using two sets of non-rotation, solar-metallicity stellar progenitors between 10.8 and 120 solar masses. In this talk, I will discuss the outcome of stellar collapse (successful explosion with formation of a neutron star or failed explosion with formation of a black hole) and its dependence on the supernova engine. In addition, I will present nucleosynthesis yields for the successfully exploding models, discuss their sensitivities, and compare the yields to observations of metal-poor stars.

We acknowledge fruitful and stimulating discussions with Matthias Hempel, Albino Perego, Matthias Liebendörfer, and Friedel Thielemann. This work was supported by the Department of Energy through an Early Career Award (grant No.SC0010263).

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Nucleosynthesis in the First Supernovae

A. Heger[1,2]

[1]Monash University, Melbourne, Australia
E-mail: alexander.heger@monash.edu

Whereas the first stars may not be directly observable in the near future, there is the possibility that some of the more energetic supernovae of these stars my become detectable by new instruments like JWST or WFIRST. A more indirect, but possibly equally efficient, way to learn about the nature of the first stars and their supernova is by looking at their nucleosynthesis. From the abundance patterns that have been preserved in some of the most metal poor stars, we may deduce the properties of the stars that made these patterns, which can be unique or characteristic to specific mass ranges or explosion mechanisms or energies. I will present models on the nucleosynthesis in primordial stars and supernovae, and how we may use them to learn about the first generation of stars in the Universe.

Gamma-ray measurements from supernovae and their radioactive afterglows

R. Diehl

Max Planck Institut für extraterrestrische Physik, Garching, Germanyy
E-mail: rod@mpe.mpg.de

The measurement of gamma rays from radioactive by-products of supernova nucleoynthesis is a rather direct probe of the conditions of nuclear burning inside the supernova. Although instruments for such measurements are complex and less developed than the ones of other astronomical windows, important results have been obtained, in particular in recent years, with prominent supernovae Cas A, SN1987A, SN2011fe, and SN2014J. We will discuss what has been learned from those measurements and gamma rays from the ^{56}Ni and ^{44}Ti isotopes, as well as the more longlived radioactivities of ^{26}Al and ^{60}Fe and the positron annihilation gamma rays.

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Supernova spectral modelling

Paolo Mazzali
Liverpool John Moores University, Astrophysics Research Institute, Liverpool/UK
E-mail: P.Mazzali@ljmu.ac.uk

I will focus on extracting information from the nebula spectra of Supernovae using synthetic spectra.

Nebular spectra probe the innermost part of the SN ejecta, which is not visible at early times owing to the high opacity. Their study yields information in the composition and morphology of the inner part of a SN explosion.

For Type Ia SNe, nebular spectra yield information about the mass and distribution of 56Ni, the ratio of stable and radioactive Fe-group elements, and teh density of the inner nebula, thus representing a probe of the ejected mass.

Additionally, for core-collapse SNe nebular spectra are essential in determining the morphology of the explosion, which can be inferred looking at the profiles of lines of different elements.

The physical width-luminosity relation(s) for type Ia supernovae favour sub-Chandrasekhar and Collision models

N. Wygoda[1,2], Y. Elbaz[2] and B. Katz[1]

[1] *The Weizmann Institute of Science, Rehovot 76100, Israel*
[2] *NRCN, P.O. Box 9001, Beer-Sheva 84105, Israel*
E-mail: nahliel.wygoda@weizmann.ac.il

The width-luminosity relation among type Ia supernovae (slower is brighter) [1] is critical for using Ia's as standard candles and is one of the best studied properties of this type of events, and yet its physical basis has not been identified convincingly. The 'luminosity' is known to be related to a clear physical quantity - the amount of ^{56}Ni synthesized, but the 'width' has not been quantitatively linked yet to a physical time scale. We demonstrate [2] that there are two robust fundamental time scales which 1. Can be calculated using simple physical considerations based on integral quantities of the ejecta and 2. Can be inferred from observations. Two physical width-luminosity relations are obtained that can be used to test explosion models with little dependence on radiation transfer modelling. The first is the gamma-ray deposition time t_0 which determines the long term evolution of the bolometric light curve and the second is the recombination time of ^{56}Fe and ^{56}Co from doubly ionized to singly ionized states which sets the long term color evolution of the emitted light. When compared to observations, these width-luminosity relations are found to be consistent with central core detonations and collisions of sub-Chandrasekhar mass white dwarfs (WDs) but not with delayed detonation models for explosions of Chandrasekhar mass WDs. We argue that the combination of narrow nebular emission lines and the bolometric constraints provides strong evidence against Chandrasekhar mass models for low luminosity type Ia supernovae and therefore as a primary source of the continuous wide distribution of type Ia supernovae.

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Polarization as a test for multi-dimensional explosion models of Type Ia supernovae

M. Bulla[1,2], S. A. Sim[2], M. Kromer[3,4], R. Pakmor[3],
S. Taubenberger[5], I. R. Seitenzahl[6], F. K. Röpke[3,4], W. Hillebrandt[7]

[1] Stockholm University, Stockholm, Sweden
[2] Queen's University Belfast, Belfast, UK
[3] Heidelberger Institut für Theoretische Studien, Heidelberg, Germany
[4] Institut für Theoretische Astrophysik, Heidelberg, Germany
[5] European Southern Observatory, Garching bei München, Germany
[6] University of New South Wales, Canberra, Australia
[7] Max-Planck-Institut für Astrophysik, Garching bei München, Germany
E-mail: mattia.bulla@fysik.su.se

Type Ia supernovae (SNe Ia) are believed to stem from the thermonuclear explosion of carbon-oxygen white dwarfs in binary systems, but answers to the questions of when, why and how these events are triggered remain unclear. In this respect, the observational evidence that SNe Ia are associated with rather low polarization signals (smaller than a few per cent) places strong constraints for models and calls for modest asphericities in the progenitor system and/or explosion mechanism. In this talk, I will discuss the power of spectropolarimetry in testing and discriminating between different explosion models of SNe Ia. In particular, I will present results for three state-of-the-art multi-dimensional explosion models that have been proposed as viable channels to explain SNe Ia. I will show that - while all the three models reproduce SN Ia light curves and spectra comparably well and would then be hard to differentiate - polarization provides a clear distinction and allows us to discriminate between the different scenarios.

Recombination Effects on Supernova Light-Curves

T. Faran[1], **R. Sari**[1] **and E. Nakar**[2]

[1]The Hebrew University of Jerusalem, Jerusalem, Israel
[2] Tel Aviv University, Tel Aviv, Israel
E-mail: tamar.faran@mail.huji.ac.il

Type II-P supernovae (SNe) are marked by the long plateau in their optical light curves. The plateau is believed to be the result of a recombination wave that propagated into the outflowing hydrogen envelope of the star, releasing the energy that was deposited in it by the shock wave. The early stages of the evolution, when the SN envelope is fully ionized, were well modeled in several analytic works. However, a description of the SN envelope in the later stages of the evolution is still lacking. In this work we analytically investigate the transition from a fully ionized envelope, to a partially recombined one, and its effects on the temperature and bolometric luminosity. We assume a simple, but adequate, hydrodynamic profile of the ejecta, and follow the diffusion of photons as they propagate through the SN envelope. Following the ionization fraction and the coupling between radiation and gas, we derive the evolution of the temperature and bolometric luminosity with time. We find that once the recombination front reaches the inner parts of the outflow, it sets the observed temperature to be nearly constant, and slows the decline of the luminosity (or even leads to a modest re-brightening). We find the power law decline of the temperature and luminosity and compare our findings to recent observational results.

Central Engines of Superluminous Supernovae and their environment

S. Blinnikov[1]

[1]NIC "Kurchatov Institute – ITEP", Moscow, Russia
E-mail: Sergei.Blinnikov@itep.ru

Large amounts of mass may be expelled by a star a few years before a supernova explosion. The collisions of SN-ejecta and the dense CSM may provide the required power of light to make the supernova much more luminous. This class of models is referred to as "interacting SNe". Many SLSNe I have photospheric velocity of order 10^4 km/s which is hard to explain in interacting scenario with modest energy of explosion. A strong "hypernova" explosion improves the situation and the properties of SLSNe near maximum light are explained by a GRB-like central engine, embedded in a dense envelope and shells ejected prior the final collapse/explosion of a massive star. In this case velocity up to $1.5\text{x}10^4$ km/s is no problem for not very long light curves. The problem remains with the nature of the central engine and evolution scenarios leading to double explosions. In view of new LIGO/VIRGO detections of gravitational waves and accompanying events, a few comments and historical remarks will be given.

Spectral Synthesis Modelling with CMFGEN

D. J. Hillier

Department of Physics and Astronomy
&
Pittsburgh Particle physics, Astrophysics, and Cosmology Center (PITT PACC)
University of Pittsburgh
Pittsburgh, PA 15260, USA
hillier@pitt.edu

CMFGEN is a 1D non-LTE radiative transfer code (e.g., Hillier and Miller 1998) originally used to model hot stars with stellar winds (O stars, luminous blue variables, Wolf-Rayet stars), but over the last decade it has been extensively revised to model supernovae (SNe) of all spectral types (Hillier and Dessart 2012). It allows for the multitude of atomic processes (such as bound-bound, bound-free, free-free, collisional, and charge exchange) that are necessary to accurately deduce the state of the gas. It also allows for excitation and ionization by non-thermal electrons created by scattering and absorption of high-energy (MeV) gamma rays. CMFGEN also treats the time-dependence of both the radiative field and the kinetic equations.

As input, CMFGEN uses the SN structure generally derived from 1D explosion models, although 1D models extracted from 2D or 3D explosion models can also be used. Apart from some smoothing (which can also induce mixing) we make no major changes to the hydrodynamical models. For Type Ia models we generally begin our CMFGEN simulations at ~1 day, but for core-collapse SNe we typically start the simulations at 10 days. The later start time in core-collapse SNe arises from our radiation transport solver which assumes homologous expansion. Routines which relax the homologous assumption have been developed but these have not yet been included in the main (and public) version of CMFGEN. For a model sequence we typically use a 10% time step, and model the SN ejecta into the nebula stage. There are typically no free parameters in the simulations once a model sequence begins – the resulting spectra and light curves depend only on the accuracy of the adopted initial hydrodynamical model and the CMFGEN calculations.

In this talk we highlight both the strengths and weaknesses of CMFGEN. We also highlight some of the successes in modelling SNe and discuss some of the uncertainties that have arisen in our SN studies.

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Supernovae from 8-12 solar mass stars: multicolor light curve simulations

A.Tolstov[1], **S. Jones**[2,3], **K. Nomoto**[1], **S. Blinnikov**[4,5]

[1] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo Institutes for Advanced Study, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan*
E-mail: alexey.tolstov@ipmu.jp

[2] *Heidelberg Institute for Theoretical Studies, Schloss-Wolfsbrunnenweg 35, D-69118 Heidelberg, Germany*

[3] *Computational Physics and Methods (CCS-2), LANL, Los Alamos, NM, 87545, USA*

[4] *Institute for Theoretical and Experimental Physics (ITEP), 117218 Moscow, Russia*

[5] *All-Russia Research Institute of Automatics (VNIIA), 127055 Moscow, Russia*

Adopting the explosion properties derived by the first-principle simulations, we perform a multigroup radiation hydrodynamics calculations of the most massive electron capture supernovae and the lowest mass iron-core collapse supernovae. The simulations use evolutionary presupernova models of different metallicity and derive the main characteristics of the explosions: multicolor light curves from shock breakout to ^{56}Co decay, photospheric velocity and temperature, spectral energy distribution. The results of simulations constrain what observational features we can expect from low-mass supernovae and help to distinguish types of their progenitors.

Modelling the spectral evolution of Supernovae.

M. Ergon[1] **and C. Fransson**[1]

[1] *Stockholm University, Stockholm, Sweden*
E-mail: mattias.ergon@astro.su.se

We present JEKYLL, a new code for modelling of supernovae (SN) spectra and lightcurves based on Monte-Carlo techniques for the radiative transfer. The code assumes spherical symmetry, homologous expansion and steady state for the matter, but is otherwise capable of solving the time-dependent radiative transfer problem in Non-Local-Thermodynamic-Equilibrium (NLTE). The method used was introduced in a series of papers by Lucy [1,2,3], and has been extended and refined in several ways. Non-thermal excitation and ionization is included and calculated using the Spencer-Fano solver by Kozma et al. [4]. Macroscopic mixing of the material, known to occur in the SN explosion, is taken into account in a statistical sense using the method by Jerkstrand et al. [5]. We apply the code to Type IIb SNe by calculating the early (before 150 days) evolution for a model previously found to give a good match to SN 2011dh in the nebular phase. Comparing to observations, the early spectra and lightcurves of SN 2011dh are reasonably well reproduced, although there are also differences. In a broader context, most observational characteristics of Type IIb SNe, spectral as well as photometric, are well reproduced by the model. Comparing to results where NLTE was partly switched off, strong effects of NLTE are seen, even on the bolometric lightcurve. This highlights the need for full NLTE calculations when simulating the spectra and lightcurves of SNe.

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The variety of pair-instability supenovae

A. Kozyreva[1], **M. Gilmer**[2], **R. Hirschi**[3], **C. Froelich**[2]

[1] *Tel Aviv University, Tel Aviv, Israel*
[2] *Keele University, Keele, UK*
[3] *North Carolina State University, Raleigh, USA*
E-mail: sasha@wise.tau.ac.il

In the talk I will show that observational properties of pair-instability supernovae (PISN) might be very different. It depends on whether the progenitor retains hydrogen, what is the radius of pre-supernova, and on amount of radioactive nickel produced in the pair-instability explosion. I will present self consistent models. Their stellar evolution was calculated with the codes BEC and GENEC, the pair-instability explosion was computed with the hydrodynamics code FLASH, and the post-explosion evolution of ejecta, light curves and observational properties were simulateds with the radiation hydrodynamics code STELLA. I will show that some low-mass PISNe (150 solar masses) look like bright plateau SNe II, others from the high-mass end (250 solar masses) are superluminous supernovae. Intermediate class of PISNe looks as slowly evolving SNe Ib. I will show a few observational examples which might be explained by pair-instability supernovae.

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Observational constraints on the explosion mechanisms of Type Ia supernovae

K. Maguire[1]

[1]Queen's University Belfast, Belfast, UK
E-mail: kate.maguire@qub.ac.uk

Linking observations of normal Type Ia supernovae (SNe Ia) to the predictions of theoretical explosion models remains a key issue in our understanding of how white dwarfs explode. I will review recent advancements in the observational properties of SNe Ia. In particular focussing on observations very soon after explosion combined with data obtained many hundreds of days later. These epochs have historically been difficult to obtain data at but probe complementary physical aspects of their explosions. I will present new results of the nucleosynthetic yields suggested by observations of SN Ia cores at late times, and how future larger samples may allow us to distinguish between different proposed explosion mechanisms.

The Spectroscopic Connection between Superluminous SNe and SN-GRBs

M. Modjaz[1], Y. Liu, F. Bianco[1]
[1] *New York University, New York, USA*
E-mail: mmodjaz@nyu.edu

Super-luminous supernovae (SLSNe) are tremendously luminous explosions whose power sources and progenitors are highly debated. Broad-lined SNe Ic (SNe Ic-bl) are the only type of SNe that are connected with long-duration gamma-ray bursts (GRBs). Studying the spectral similarity and difference between the members of the SN Ic family, namely the hydrogen- poor SLSNe (SLSNe Ic) and hydrogen-poor stripped-envelope core-collapse SNe, in particular SNe Ic and SNe Ic-bl, can provide crucial observations to test predictions of theories based on various power source models and progenitor models. We present the most thorough spectroscopic analysis (using new tools we developed) using the largest public spectroscopic dataset of 32 SLSNe Ic, 21 SNe Ic-bl, as well as 17 SNe Ic. We discuss our insights and constraints on the connection between SN-GRBs and SLSNe in terms of their spectra as well as their progenitor models, and in addition discuss whether specific SNe, such as 2011kl which was connected to an ultra-long GRB, are typical SLSNe.

Supernova physics from spectrophotometric data

J. Nordin[1]

[1]*Humboldt Universität zu Berlin, Berlin, Germany*
E-mail: jnordin@physik.hu-berlin.de

The Nearby Supernova Factory has obtained spectro-photometric time-series of both Type Ia and core collapse supernovae. I here summarize the many ways in which these data can be used to probe SN physics. These topics include: (i) estimations of ejecta and Ni mass through bolometric lightcurves (ii) new spectroscopic features probing temperature profile and Ni distribution (iii) what can be learned from twin supernovae (iv) a completely data-driven determination of dust and intrinsic reddening and (v) measurements of the local environment. These data provide evidence both for strongly varying ejecta masses and that the SNIa photometric decline rate (but not peak magnitude) depends on the progenitor age in a way that bias traditional SN standardization for cosmology. I also discuss what future observations could further probe these questions, and to what extend spectro-photometry is required.

Multi-band observations of the closest type I superluminious supernova 2017egm/Gaia17biu in a "normal" metal rich spiral galaxy

S. Bose[1], S Dong[1], A. Pastorello[2], A. V. Filippenko[3], C. S. Kochanek[4], J. Mauerhan[3], C. Romero-Canizales[5], NUTS & ASAS-SN collaboration

[1] *Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing, China*
[2] *INAF-Osservatorio Astronomico di Padova, Padova, Italy*
[3] *Department of Astronomy, University of California, Berkeley, USA*
[4] *Department of Astronomy, The Ohio State University, USA.*
[5] *Millennium Institute of Astrophysics, Santiago, Chile.*
E-mail: bose@pku.edu.cn

Hydrogen-poor superluminous supernovae (SLSNe-I) are a rare class of events whose explosion mechanism is not well understood. Existing studies suggest a strong bias in production efficiency of these events towards low-metallicity and dwarf galaxies. Here we present detailed multi-band observations for a SLSN-I Gaia17biu, which we identify in a ``normal" spiral galaxy (NGC 3191) in terms of stellar mass (several times 10^10 M_Sun) and metallicity (roughly solar). At a redshift z=0.031, the SN is the closest SLSN-I discovered till date. Due to the proximity of the SN, implying highest apparent brightness for a SLSN-I, we are able to study Gaia7biu in an unprecedented detail. Its pre-peak near-ultraviolet to optical color is similar to that of Gaia16apd and among the bluest observed for a SLSN-I, while its peak luminosity (M_g = -21 mag) is towards the low end of the SLSN-I luminosity function. From our high signal-to-noise ratio spectra, we could identify several new spectroscopic features that may help to probe the properties of these energetic explosions. Our spectropolarimetric observations reveals a polarization of ~ 0.5% with no strong wavelength dependence, suggesting a modest, global departure from spherical symmetry for the source. In addition, we put the tightest upper limit yet on the radio luminosity of a SLSN-I at <5.4 x 10^26 erg/s/Hz (at 10 GHz), which is almost a factor of 40 better than previous upper limits and one of the few measured at an early stage in the evolution of an SLSN-I. This limit largely rules out an association of this SLSNe-I with known populations of gamma-ray bursts (GRBs). The upper limits of Radio and X-ray non-detections likely suggest the absence of any strong CSM interaction.

High-Cadence Light-Curves with Kepler, TESS, and GLUV

Brad E. Tucker[1,2]

[1]Mt Stromlo Observatory, the Australian National University
[2] ARC Centre of Excellence for All-Sky Astronomy (CAASTRO)
E-mail: brad@mso.anu.edu.au

High-cadence (> 1 hour) light-curves are now a reality of modern day supernova (SN) searches and open a new window into SN physics. The 30-minute cadence of Kepler has revealed subtle features in the light-curves of supernova not detectable with any other survey, including, shock break-out in a large number of SN, improving our understanding of supernova progenitors. We can also search in nearby galaxies for fast and faint transients, filling in a previously inaccessible parameter space. With the imminent launch of TESS, the community is likely to have over 100 well-sampled SN of multiple types. Lastly, a new UV survey mission GLUV will provide high-cadence light-curves in the UV.

ZTF and supernovae from PTF

Jesper Sollerman[1]

[1] *OKC, Stockholm University, Sweden*
E-mail: jesper@astro.su.se

I will probably talk about some of the supernovae we have found and followed with the Palomar Transient Factory (PTF) the past couple of years, and think ahead about what we can do with the upcoming ZTF survey. Among the supernovae, I will mention those where I hope modelers and theoreticians can help out to interpret the results. How can we understand the very late emission from Type II iPTF14hls, Type IIn 13z or Type Ic 15dtg? What does the very early spectra of core-collapse supernovae tell us? Do we know if Type Ib/c supernovae come from very massive single progenitors or from binary star systems? More questions than answers here..