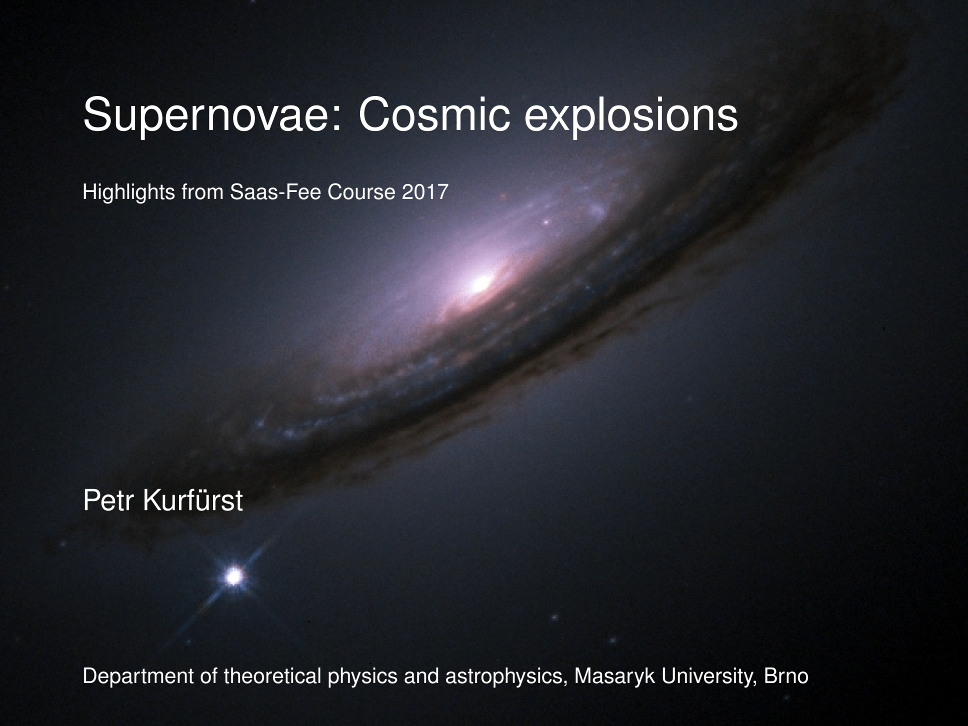

Supernovae: Cosmic explosions

Highlights from Saas-Fee Course 2017

Petr Kurfürst

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Thermonuclear supernovae

Friedrich Röpke
Heidelberg Uni

Current research outputs:

- thermonuclear SNe explosions
- explosions of “light massive stars”
- SNe Ia are rather a class of astrophysical observations
- most likely not all theoretical models are realized in nature
- not sure the current models can explain all SNe Ia
- no equivalence: Thermonuclear SNe $\not\Leftrightarrow$ Type Ia SNe

Thermonuclear supernovae

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Heidelberg Uni

Current research outputs:

- rise time 19 days
- maximum of luminosity: $L_{\mathrm{bol,max}} \approx 10^{43}\,\mathrm{erg\,s^{-1}} = 10^{9.4} L_{\odot}$
- total radiated energy: $E_{\mathrm{rad}} \approx 10^{49}$ erg, total kinetic energy: $E_{\mathrm{kin}} \approx 10^{51}\,\mathrm{erg} \Rightarrow E_{\mathrm{kin}} \approx 10^{2} E_{\mathrm{rad}}$
- fade away over days, weeks and months
- maximum emission in visible light, in range of V and B filters
- no traces of H, He in spectra, strong features of intermediate elements (S, Si) and iron group (Ni, Co, Fe)

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- maximum emission in visible light, in range of V and B filters
- no traces of H, He in spectra, strong features of intermediate elements (S, Si) and iron group (Ni, Co, Fe)
- no direct observations of progenitor systems, nature of progenitors remains elusive
- explosion of stellar objects: why?
- spectral lines shift $\rightarrow$ high velocities $\approx 10^{4}\,\text{km}\,\text{s}^{-1}$

Thermonuclear supernovae

Energy release of SNe Ia:

- gravitational binding energy
  - liberated in shrink or collapse - assume sphere of a uniform density
    $\Rightarrow E_g = \frac{3}{5} G \frac{M^2}{R} \approx 10^{53}\mathrm{erg}$
  - SNe Ia associated with low mass stars
  - degenerate core forms below critical mass $M_{\mathrm{Ch}} \approx 1.44\, M_{\odot}$

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- nuclear energy of material
  - initial ejecta - dense and opaque to radiation
  - takes several days before all energy produced in interior by $^{56}\mathrm{Ni}$ decay reaches the "surface" $\rightarrow$ shapes light curve and peak of L
  - simplifying assumption: mass of produced $^{56}\mathrm{Ni} \approx 0.6\,M_\odot \Rightarrow$ LC picture around peak of L powered by $^{56}\mathrm{Ni}$ decay beyond doubt
  - evolution of Ni/Co/Fe ratio: $^{56}\mathrm{Ni} \xrightarrow{t_{1/2}=8.8\,\mathrm{d}} {}^{56}\mathrm{Co} \xrightarrow{t_{1/2}=78.8\,\mathrm{d}} {}^{56}\mathrm{Fe}$,
    $^{57}\mathrm{Ni} \xrightarrow{t_{1/2}=35.6\,\mathrm{d}} {}^{57}\mathrm{Co} \xrightarrow{t_{1/2}=271.8\,\mathrm{d}} {}^{57}\mathrm{Fe}$,
    $^{55}\mathrm{Co} \xrightarrow{t_{1/2}=17.5\,\mathrm{h}} {}^{55}\mathrm{Fe} \xrightarrow{t_{1/2}=1000\,\mathrm{d}} {}^{55}\mathrm{Mn}$

Thermonuclear supernovae

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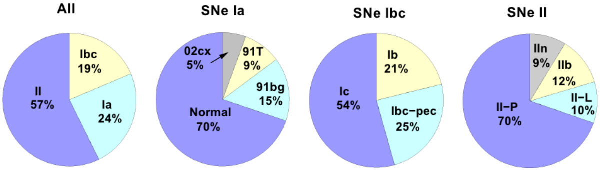
Questions: how different are type Ia SNe ?

- $\approx$ 70% majority of SNe Ia likely normal CO M_{Ch} WDs
- but: well-known outliers: SN 1991T, SN 1991bg
- wide range of events that significantly diverge from the standard



Pie charts show the observed fractions of each type of supernova in a volume-limited sample

- one or many explosion scenarios ?
- demands on a valid model: ability to explain a certain sub-class

Thermonuclear supernovae

Properties of type Ia SNe ?

- type Ia SNe $\rightarrow$ bright $\rightarrow$ “standard candles” $\rightarrow$ cosmological distance determination, evolve on “human” timescales
- “Brahe”, “Kepler” $\rightarrow$ probably type Ia Sne
- contribution to Galaxy chemical evolution:
  - SNe Ia produce $\approx 0.5 M_\odot$ of Fe per 1 event
  - cc SNe produce $\approx 0.1 M_\odot$ of Fe per 1 event
  - about 2/3 of Fe in local! universe made by SNe Ia

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- SN Ia cosmology tests “world model”: revolution - Riess 1998, Perlmutter 1999
  - SNe distances incosistent with any universe dominated by gravity
  - can only be fitted by model involving Λ
  - expansion accelerates

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- precise SN Ia distance measurements $\rightarrow$ major task
- dark energy $\rightarrow$ major challenge to theory

Thermonuclear supernovae

Are SNe Ia standard candles ?

- no, even if most observed SNe Ia are “normal”
- significant variations among “normal” SNe Ia $\rightarrow$ peak brightness $\sim$ order of mag $\rightarrow$ large errors in, if uncorrected (stretch parameter)
- prominent empiric relation between $M_{B,\mathrm{max}}$ and shape of LC, no theoretical background !

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  - precise theoretical understanding of WLR
  - dependence on environment, metallicity ?
  - different progenitor/explosion mechanisms ?

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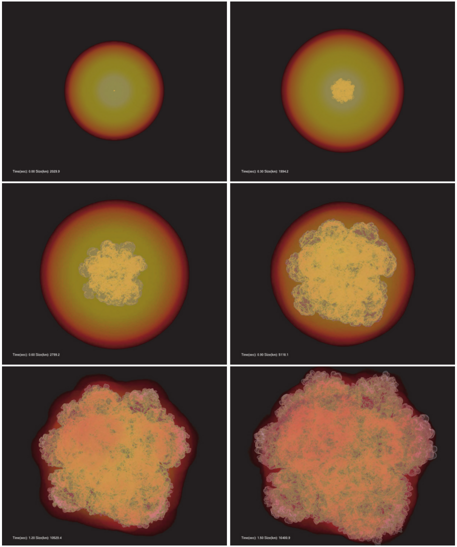
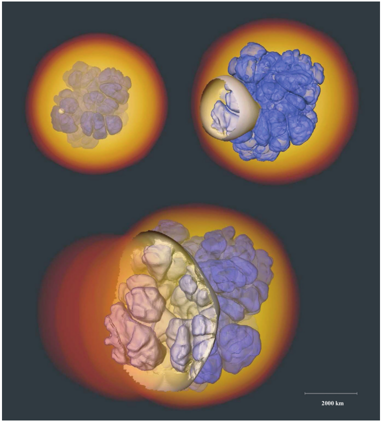
- 1D models $\rightarrow$ best fit observations (tuned to fit astro data)
- but: there are intrinsically multi-D processes $\Rightarrow$ multi-D models $\rightarrow$ explosion mechanisms, connection to progenitor structure and evolution, nuclear processes, etc.

Thermonuclear supernovae



Deflagration simulation 0 s, 0.3 s, 0.6 s, 0.9 s, 1.2 s, and 1.5 s after ignition (F. Röpke)

Thermonuclear supernovae



Visualization of the delayed detonation simulation at the onset of the detonation phase: 0.72 s (top left), 0.80 s (top right), and 0.90 s (bottom) after the ignition of the deflagration flame, which is shown as a blue isosurface. The detonation front is indicated by the white isosurface and volume-rendered (yellow/orange) is the density of the exploding WD star (F. Röpke)

Thermonuclear supernovae

Progenitors and ignition of thermonuclear SNe:

- favored progenitor scenario: CO WD $\rightarrow$ why ?
  - most abundant
  - thermonuclear burning most likely to produce SN Ia - like event
  - why not He WDs ? $\rightarrow$ would show He in spectra, what about ONe WDs ?

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- after ignition of C (O) burning $\rightarrow$ energy transported out of center by convective motions
  - off-center ignition ? $\rightarrow$ radius of about 50 km
  - ignition in sub-M_{Ch} WDs less natural than in M_{Ch} WDs $\rightarrow$ other process is necessary (e.g., He detonation in envelope driving a shock wave towards CO core)
  - super-M_{Ch} WDs ?? $\rightarrow$ WD mergers (model of $0.9M_{\odot} + 1.1M_{\odot}$ $\rightarrow$ good candidate for SN Ia $\rightarrow$ produce $0.62M_{\odot}$ of ^{56}Ni), supported mass by rotation, extremely strong magnetic fields ??

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- Main modeling problems and uncertainties:
  - initial conditions uncertain $\rightarrow$ parameters of WDs vary from object to object
  - uncertainty in ignition geometry + RT, KH instabilities
  - scaling problem $\rightarrow$ thickness of combustion wave $\leq$ 1 mm for high ρ_{fuel}

Conclusions of thermonuclear SNe

- nuclear reactions not in TE as in stellar evolution $\Rightarrow$ fluid dynamical effects propagate in time as a combustion front
- nuclear reactions occur in rapidly expanding material $\rightarrow$ EOS very complex (involved as a table)
- metallicity of ZAMS progenitor of WD has significant impact on Y_e in NSE $\rightarrow$ metallicity reduces the brightness of thermonuclear supernovae
- numerical simulations - required to solve full system in 3D - extremely computationally costly
- major scaling problems $\rightarrow$ thickness of combustion wave (waves ?) $\rightarrow$ involving relevant (or even fundamental) nonlitiarities - RT, KH instabilities, turbulence, etc.

Core-collapse supernovae

Chris Fryer
LANL

Explosions from stellar collapse modeling problems:

- hydrodynamics and turbulence - post bounce conditions
- regions of instabilities, innermost ejecta decelerates $\rightarrow$ falls back $\rightarrow$ convective engine $\rightarrow$ shock decelerates $\Rightarrow$ reverse shock (dimensional analysis) $\rightarrow$ even if SN is exploding, material accretes onto proto-NS
- convection $\Rightarrow$ explosion energy up to 100 foe (most of them $\sim$ 1 foe)
- EOS $\rightarrow$ dense nuclear matter
- neutrino transport and corresponding cross sections $\rightarrow$ Boltzmann equation, numerical transport techniques
- nuclear burning
- magnetic fields $\rightarrow$ affect the fluid flow, strong B fields in proto-NS can alter the ν transport
- GR

Core-collapse engine is a multi-physics problem (slow improvement)

Core-collapse supernovae

GRBs:

Chris Fryer
LANL

- explosion from stellar collapse $\rightarrow$ search for new engines
- discovery of GRBs $\rightarrow$ VELA satellites (1967, published 1972), 1972 - 1991 $\rightarrow$ golden era for theorists
- 3 classes of GRBs:
  - solar system
  - galactic
  - cosmological
- physics ranging from accretion onto compact object (NS, BH) to cosmic strings $\rightarrow$ energy requirements vary over 20 orders of magnitude
- BATSE (satellite) results: isotropy $\rightarrow$ cosmological model favored !
- main new engine predictions: beamed explosion, “failed” SN, mergers, hyperaccreting BHs
- supernova signatures: believe $\rightarrow$ short GRBs $\Leftarrow$ compact mergers
- the difference between long and short GRBs may be the progenitor, not the engine

Core-collapse supernovae

Chris Fryer
LANL

GRBs:

- new collapse engine requirement:
  - convection appears to be crucial for the puzzle
  - magnetars $\rightarrow$ energy set by rotation
  - black hole accretion disk engine (BHAD) $\rightarrow$ high luminosities of outer layers
  - neutron star accretion disk engine (NSAD) $\rightarrow$ ultra-fast spins to work
- BHAD model seem to explain GRB data, but other engines (NSADs, magnetars) can be tuned to match data as well
- as scientists realized that the magnetic fields mechanism cannot explain GRBs, they adapted to SNe
- test: energetics $\rightarrow$ standard mechanism 1, NSADs/magnetars 0
- but perhaps these engines work for exotic SNe (SLSNe)

Core-collapse supernovae

Asymmetries in SNII explosions

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LANL

- asymmetries in collapse $\rightarrow$ may cause kicks
- asymmetries in convective engine $\rightarrow$ large-scale mixing in O/Si burning, rotation $\Rightarrow$ convection enhanced (limited to) in polar regions
- asymmetries in convection and neutrino-heating cause asymmetries in SN explosion
- instabilities in 3D models $\rightarrow$ large kicks $\rightarrow$ fast moving pulsars
- observational tests: $\rightarrow$ pulsar velocities, measurements of γ-ray emissions, gravitational waves, etc.
- SN asymmetries
  - bimodal $\Leftarrow$ B fields and magnetars, strong rotation
  - chaotic $\Leftarrow$ convection
  - further evidence of ^{44}Ti distribution $\rightarrow$ unique tracer of the explosion $\rightarrow$ maps the convection $\rightarrow$ excellent probe of the engine
  - Cassiopeia A: $^{44}Ti \rightarrow {}^{44}Ca + \gamma$ rays (NUSTAR detection) distribution $\rightarrow$ the explosion cannot be jet-like $\rightarrow$ rules out B fields and rotation

Core-collapse supernovae

Anatomy of CC SN light curve

- mass ejecta prior to collapse $\rightarrow$ explosive winds, binary interactions... can produce shells/clumps of CS media
- Caution with using LC as probes:
  - by varying characteristics, the models may not be unique
  - CS media may alter the LC
  - RHD in shocks $\rightarrow$ even when the radiation is trapped, it can lead the shock $\rightarrow$ the shock position moves faster than the Sedov solution would predict
  - most atomic physics calculations underestimate the number of very narrow lines $\Rightarrow$ accounting it, the opacity can increase dramatically!
  - opacity experiments: recent iron experiments do not agree with state-of-the-art atomic physics $\Rightarrow$ Kurucz results have trouble getting agreement with the atomic physics community
  - shock interactions with wind features/companion $\rightarrow$ companion interactions seem to have minimal effects on LC, wind interactions are much more effective

Core-collapse supernovae

Neutrinos

- neutrino physics $\rightarrow$ Burrows 1998, Fryer 2009
- EOS plays an important role in number of aspects of SN explosion:
  - bounce
  - convection in core
  - neutrino emission and opacities
- rotating stars produce a disk around PNS $\rightarrow$ how does this affect a neutrino transport?
- collective neutrino oscillations $\rightarrow$
- alternate engines $\rightarrow$ exist, but most invoking magnetic fields, magnetars, collapsars or similar mechanisms $\rightarrow$
- these do not explain normal SNe $\rightarrow$ likely $\rightarrow$ bizzare SNe or GRBs

Core-collapse supernovae

Gravitational waves

- as massive objects move around, the changes in space-time propagate as GWs $\Rightarrow$ produced in system with rapidly moving quadrupole moment
- advanced LIGO: measurements up to 200 - 215 Mpc
- most sources seen to 100 kpc
- source simplifications:
  - mild (normal) rotation and no rotation: rotating quadrupole
  - higher rotation $\rightarrow$ bar modes
  - highest rotation $\rightarrow$ fragmentation $\Rightarrow$ (better understand the convective GW signal)
- we can (even with advanced LIGO) probe the convective signal only for Galactic SNe
- a range of possibilities for CC: convection, rotation, bar-modes, *r*-modes, BH ringing ?

Conclusions of CC SNe

A lot of future work:

- progenitors
- EOS and neutrino physics
- transports and turbulence
- magnetic fields
- advancing neutrino and GW signals
- LCs $\rightarrow$ understand uncertainties and produce more accurate models
- nucleosynthesis $\rightarrow$ beat down uncertainties

Various rate of SN events within various galaxies ?

- MW $\rightarrow$ last SN: 1604, M31 $\rightarrow$ last SN: 1885A
- NGC 6946 (fireworks galaxy, $D = (6.9 \pm 3.4)$ Mpc) SNe: 1917A, 1939C, 1948B, 1968D, 1969P, etc.

Thank you for attention