Galaxy Feedback

Cosmology: Distance Ladders

Chemical Enrichment

First sources of ionizing photons

Galaxy Feedback

Deposition of Radiative+ Mechanical Energy

Explosive Transients

Endpoint of Stellar Evolution

Laboratories of Extreme Physics (jets)

They produce the most Extreme Objects

Sources of GWs and Neutrinos
High-Energy emission from Transients

- Tidal Disruption Events
- Engine-Driven SNe / GRBs
- Strongly Interacting SNe
- SuperLuminous SNe
The flattening, the profile appears to recover to the central parsec of the Milky Way Galactic center from the observed X-ray luminosity indicates that the fraction of total energy emitted in the band. Such a break is indicative of the synchrotron cooling free templates are not presently available. We estimate the continous X-ray count rates in the spectra that span over multiple decades. As such, a ma−1. To explain the escape of activity close to the sequene of their inactive nature, it is more difficult to be able have been suggested to show some signs of periodicity have been suggested to show some signs of periodicity.
High-Energy emission from Transients

- Tidal Disruption Events
- Engine-Driven SNe / GRBs
- Strongly Interacting SNe
- SuperLuminous SNe
Energy partitioning

SNe are an OPTICAL phenomenon

- $10^{51}$ erg OPTICAL
- $10^{47}$ erg X-rays/Radio
- Ordinary SNe 1bc

Margutti +13, +14; Kamble +13; Soderberg +06, +10
The restless
SN2009ip

.....Once upon a time SNe exploded once....
Distance of 24 Mpc

In the outskirts of NGC7259

Sub-solar metallicity environment 0.4<Z<0.9 Zsun

Discovery Aug 2009

Outburst Jul 2010

Outburst Sep 2010

Outburst May 2011

Outburst Oct 2011

Supernova Aug 2012

Supernova Sep 2012

Supernova Impostor Aug 2012

Supernova Oct 2012

Explosion1

Explosion2
Eruptions

UV-Optical-NIR light-curve

Margutti+ 2014
Expected Evolution from Stellar tracks:

- Luminous Blue Variable (Eruptions)
- Wolf-Rayet
- SN Explosion

15-20 days

MASS LOSS – Massive Stars

SN Luminosity

Time

10^4 - 10^5 yrs
A new channel of Explosive Mass Loss in evolved massive stars

Supergiant

Luminous Blue Variable (Eruptions)

Wolf-Rayet ~10^4 - 10^5 yrs

SN Explosion

A supernova symphony unraveled?

SN2009ip

Margutti Astronomy Magazine
"It sort of makes you stop and think, doesn't it."
SN shock
strong interaction w.
medium

See Murase+ 2011
Massive star: \( M > 60 \text{ Msun} \)

Smith et al, 2010; Foley et al., 2011
Developing STRONG interaction....

...in real-time...
Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

SN Luminosity vs. Time

15-20 days
Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

Density

R ~1d15 cm

Type IIP iPTF13dqy

Red Supergiant

Radius

Yaron+2017
Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

Supergiant

Wolf-Rayet

\(-10^4-10^5\) yrs

SN Explosion
Enhanced and Episodic Mass-Loss

Direct Observations

Flash Spectroscopy

Shock Interaction

Radio

X-rays

Radio

X-rays

Radio

X-rays
Enhanced and Episodic Mass-Loss

- Direct Observations
- Flash Spectroscopy
- Shock Interaction
Type I  
H-poor

Type II  
H-rich

SN2014C

Tinyanont et al., 2016  
Anderson et al., 2016  
SN2014C: a normal Ib SN

Dist = 15.7 Mpc

Bolometric Luminosity

Optical Spectrum at max

SN 2014C

t = -2 d

SN 2008D (Ib)

RM+16

Dist = 15.7 Mpc

Bolometric Luminosity

Optical Spectrum at max

SN 2014C

t = -2 d

SN 2008D (Ib)

RM+16
Development of H-features with time

SN2014C-Optical

Milisavljevic, RM+16
Radio Luminosity INCREASES w. time!
SN2014C-X-rays (soft+hard)

Rising X-ray Luminosity!
NuSTAR (3-80 keV)

SN2014C

NUSTAR FPMA 2015 Aug 23 Exposure: 30225 s

SN2014C
Exploding Star challenges decades-long understanding of how massive stars evolve and die

Credit: NASA/CXC/CIERA/R.Margutti et al

#space
http://go.nasa.gov/2jWc8Ua
Type I SN

Type II SN

RM+16

Type I SN

Type II SN
Direct Constraints on the shock dynamics!
Density

Radius

R \sim 5 \times 10^{16} \text{ cm}

H-poor medium

High-density H-rich medium

\sim 1 \text{ M}_\odot
Expected Evolution from Stellar tracks:

- Supergiant
- Wolf-Rayet
- SN Explosion

\[ \text{~}10^4\text{--}10^5 \text{ yrs} \]

Density vs. Radius

Hydrogen

H-free!!!
Expected Evolution from Stellar tracks:

Supergiant → Wolf-Rayet → SN Explosion

- $10^4 - 10^5$ yrs

MASS LOSS – Massive Stars

Density

Hydrogen

H-free!!!
Expected Evolution from Stellar tracks:

- Supergiant
  - Wolf-Rayet
  - SN Explosion
    - \(10^4 - 10^5\) yrs

Nuclear Burning Instabilities

MASS LOSS - Massive Stars
Non thermal Radio emission Ibc
New class of high-energy transients from crashes of supernova ejecta with massive circumstellar material shells

Kohta Murase,1,2 Todd A. Thompson,1,3 Brian C. Lacki,1,3 and John F. Beacom1,2,3
Super-Luminous SNe

What Source of Energy powers SLSNe?

\[ E_{\text{rad}} = 10^{51} \text{ erg} \]
\[ E_{\text{K}} = 10^{52} \text{ erg} \]
What powers SLSNe?

**Interaction**
- E.g. Chevalier 2011
- Pan & Loeb 2013

**56Ni**
- Gal-Yam 2009

**Magnetar**
- Kasen & Bildsten 2010
- Woosley 2010

**Increased Efficiency**
- Pan & Loeb 2013

100 days!
What powers SLSNe?

Interaction
E.g. Chevalier 2011
Pan & Loeb 2013

$^{56}\text{Ni}$
Kasen & Bildsten 2010
Gal-Yam 2009

Magnetar
Woosley 2010

"The problem is completely specified by the properties of the pulsar and of the ejecta"
Metzger 2013
Observing Proposal 2015/2016

Proposal Title: A new window of investigation on strongly interacting SN shocks: VERITAS observations of SN2014C
Science Group: DM-Aspen
Authors: M. Cerruti, W. Benbow (Harvard), R. Margutti (NYU), K. Murase (Penn State U), N. Omodei (Stanford U), T. Cheung (Naval Research Lab.), D. Milisavljevic (SAO), A. Kamble, J. Parrent, A. Zauderer, (Harvard), R. Chornock (Ohio U), W. Fong (Arizona U)

1. Scientific Justification
Optical transient surveys recently revealed a new class of strongly interacting supernovae (SN), characterized by the presence of extremely dense material ($n > 10^6$ cm$^{-3}$) close to the progenitor ($d < \text{a few } 10^{16}$ cm). For these SNe, the explosion's shock does not break out from the edge of the star. Instead, the shock breaks out in the wind, where the optical depth is $\tau_{\text{op}} \approx c/v_{\text{shock}}$. The breakout signal thus carries unique information about the progenitor mass-loss history during the years preceding the explosion. The mass-loss history of massive stars is poorly understood and yet is a fundamental parameter that drives their evolution (Smith 2014). With this program we will shed new light on this phenomenon capitalizing on our multi-band campaign of SN2014C. Our study opens a new window of investigation on the SN shock breakout physics.

Recent observations indicate that $\approx 10\%$ of massive stars are unexpectedly surrounded by thick shells of material at the time of their explosion (e.g. Smith 2009). This conclusion is supported by two key observational findings from our team: (i) the remarkable double explosion of SN2009ip in 2012 (Margutti 2014); (ii) the unprecedented metamorphosis of SN2014C, which evolved from a type I to a type II SN (Fig 1-2) as a consequence of strong interaction with H-rich material.

These facts imply that: (i) The ejection of massive shells in the last stages of stellar evolution is a common mechanism whose physical origin has still to be understood (Margutti 2014). This is indeed one of the major challenges faced by current theories of stellar evolution. (ii) At the moment of the SN explosion, a significant fraction of kinetic energy is dissipated (and radiated) by the collision of the SN ejecta with the circumstellar medium (CSM). (iii) As the SN ejecta crash into the massive shells, very high energy (VHE) emission is also produced, with a fluence that directly depends on the CSM shell parameters (mass, radius), ejecta parameters (mass and energy) and on the - still unknown - efficiency of acceleration of cosmic rays by SN shocks (Murase 2011, 2013; Katz 2012). (iv) The same process also produces neutrinos (Murase 2011, 2013), putting interaction-powered SNe among the most promising targets for the upcoming generation of neutrino detectors.

Thus motivated, we propose a VERITAS program to observe SN2014C, the most promising candidate for VHE from a young and strongly interacting supernova shock in the last decade, with the aim to: (1) Test the SN shock breakout through a dense wind model using VHE observations. (2) Constrain the cosmic rays (CR) acceleration at shocks formed by the collision between the SN ejecta and the CSM shell. (3) Deliver the first predictions of the associated neutrino emission.

A solid prediction of the SN shock breakout model is the presence of bright VHE emission produced as the SN ejecta crash into previously ejected material (Murase 2011; Katz 2012), with a typical duration of months to years (Fig. 1). As the SN shock breaks through the thick CSM shell a bright peak of UV-optical emission is produced, as a consequence of efficient conversion of kinetic energy into...
“...The END

is where we start from...”

The Little Gidding by T.S. Eliot

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