Observations of the Ghosts of Dead Stars

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Hubble Science Briefing

The Ghost of SN 1006 AD
A Word about Hubble (and other) pictures…

• Each color image is made up of MANY individual exposures, with each color representing the light from a different filter or instrument.

• Each filter captures light from a certain color of star or emission component of the gas.

• Primary colors combine in places to show where multiple emissions are present.

Crab Nebula M1
HST WFPC2

Crab Nebula
July 4, 1054 AD

(24 WFPC2 Fields in multiple filters stitched together into one picture!)
Most Kinds of Light are only visible from space

- Gamma-ray
- X-ray
- UV
- Infrared
- Optical
- Radio

Graph showing the atmospheric opacity across different wavelengths, with Chandra, Hubble, and Spitzer satellites indicated.
For visible light, Why go to Space?

M83: Ground-based image (Photo: Rob Gendler)

M83 with Hubble/WFC3

Better spatial resolution! (Can see finer details.)
There’s nothing like having high spatial resolution!

A small portion of ground-based H\(\alpha\) data in the nearby galaxy M83.

2004

Ground-based H\(\alpha\)
2009

Hubble/WFC3 H\(\alpha\) data
2010

(More later.)
Gas pressure comes from nuclear fusion reactions deep in the core of the star.  

\[ E = M \times C^2 \]  
(Energy = mass x const.)

4H atoms → He + Energy

1 gram H → He + 0.007 grams converted to Energy
Different Results for Stars of Different Mass

Low Mass Stars
- Red Giant Star
  - Inert Fe-Ni Core
  - H Burning Shell
  - Cool, Extended Envelope
- Ring Nebula
- Expanding at 10 km/s
- Planetary Nebula & white dwarf star

High Mass Stars
- End of the Silicon Burning Phase
  - H Burning Shell
  - He Burning Shell
  - C Burning Shell
  - Ne Burning Shell
  - O Burning Shell
  - Si Burning Shell
- Core Radius: $\sim 1 \, R_{\text{Earth}}$
- Envelope Radius: $\sim 5 \, \text{AU}$

Cassiopeia A
- 340 years after explosion.
- Expanding at more than 10,000 km/s!

Supernova Explosion & (possibly) pulsar or BH
Star Evolution, SNRs, and the ISM
Large Magellanic Cloud - 170,000 ly away

Data from the Magellanic Cloud Emission Line Survey (MCELS) project, C. Smith, PI
Large Magellanic Cloud - 170,000 ly away

SN1987A
Feb. 1987

The remains of a 20 solar mass star!
SN 1987A - A Young Ghost!

Have been able to watch the evolution of the supernova over time!


- September 24, 1994
- March 5, 1995
- February 6, 1996
- July 10, 1997
- February 6, 1998
- January 8, 1999
- April 21, 1999
- February 2, 2000
- June 16, 2000
- November 14, 2000
- March 23, 2001
- December 7, 2001
- January 5, 2003
- August 12, 2003
- November 28, 2003

NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)
Details are Still a Mystery

- No sign of central neutron star or black hole!
- Still don’t really understand the rings.

One theory of the evolution of Supernova 1987A (SN 1987A)

1. A binary stellar system. The more massive (primary) star evolves first.

2. As the primary star becomes a giant, it engulfs its companion. The core of the primary and the companion are in a "common envelope."

3. As the companion spirals in, it ejects the envelope, mostly in the orbital plane. The companion merges with the core.

4. A fast wind from the core interacts with the torus around it, forming a ring of denser material.

5. The primary star explodes as a supernova, causing the inner edge of the ring to glow.

6. Ejecta from the explosion start to move outward.

7. The bubble of ejecta grows, approaching the inner edge of the disk.

8. The ejecta strike and shock the inner ring at an increasing number of spots, which light up on impact.
Kepler’s SNR
Multiwavelength View

Kepler’s Supernova Remnant - SN 1604

- Was a Type Ia SN, but some peculiar properties…

Hubble/ACS view -- 2003
Faint shocks have high velocities up to ~2000 km/s

Bright Radiative shocks
\( V_s > 100 \text{ km/s} \)

Dense knotty type filaments

\( N_e > 1000 \text{ cm}^{-3} \)

High N/H compared to solar.

- Broad range of densities and shock velocities--complex, highly structured *circumstellar* medium (not expected around a Type Ia SN).
Proper Motion Distance

- Before Hubble: distance estimates ranged from 8800 - 21,000 ly [2.7 - 6.6 Kpc].

- **Green**: 2003 Hubble/ACS Hα image aligned and smoothed to ground-based resolution.
- Motion: 1.45” +/-0.3” in 16.3 years.
- \( V_s = 1660 \ [\pm 120] \) km/s
- \( D = 12,700 \) ly [3.9 Kpc]
- 2nd epoch of Hubble data could significantly reduce uncertainty in motion measurement and improve the distance estimate further.

Crab Nebula
The leftovers of an 8 - 10 $M_{\text{sun}}$ Star

Distance 6500 ly
Diameter = 5x7 ly
$V_{\text{exp}} = 1800$ km/s (4 million mph!)
Contains a “stellar remnant,” a 1.4 solar mass neutron star that spins 30x per second! Strong magnetic field ---> a pulsar!
Crab Nebula Filament Details

Note “fingers” of gas, color changes represent density and ionization changes.
Multiwavelength Cas A

Cassiopeia A Supernova Remnant
NASA / JPL-Caltech / O. Krause (Steward Observatory)
ssc2005-14c

Spitzer Space Telescope • MIPS
Hubble Space Telescope • ACS
Chandra X-Ray Observatory
Cas A with Hubble
Leftovers of a ~30 $M_{\text{sun}}$ Star
Cas A Filament Close-ups

F850LP  F675W  F450W
[SIII]  [O II]+[S II]  [O III]
3 Massive Star Ghosts
(“Oxygen-rich” SNRs)

Cas A (our Galaxy)
1E0102-7219 (SMC)
N132D (LMC)
Massive Star Ghosts
Correct Relative Sizes

Cas A: ~340 years
5.6 pc (16 ly)
$V_{\text{exp}} = 8$-$12,000$ km/s

E0102: ~2000 years,
12.6 pc (41 ly)
$V_{\text{exp}} = 2,000$ km/s

N132D: ~3150 years, 25 pc (82 ly)
$V_{\text{exp}} = 800$-$1,000$ km/s (O-rich)

H$\alpha$ (HST)  [O III] (HST)  X-ray (Chandra)
Cygnus Loop -- an old Ghost

Distance about 1760 ly [2500 ly]

Diameter = 85 ly [115 ly]

Age \( \sim 5,000 \text{ yrs} \) [\( >10,000 \text{ yrs} \)]

“Only” expanding at 300 km/s (1 million mph!)

It has almost finished returning its contribution to the ISM for the next generation of stars.

How do we know the distance and size? *Hubble!*

(Ground-based optical light image)
Cygnus Loop - Hubble Detail

Spectrum provides shock speed

170 km/s
Cygnus Loop Distance

Angular motion: 0.070” +/- 0.008” per year

Using $V_s = 170$ km/s, $D = 1760$ ly
(*not* 2500 ly, which had been used for 40 years!)

A correction of 30%.
Distant Cousins?

N132D: Diameter = 82 ly

Cygns Loop: Diameter = 85 ly (not 115 ly!)
M83 Basics

Dist = 14.9 Mly
1” = 1/3600 deg = 72 ly
Barred spiral galaxy with a starburst nucleus
(a.k.a. NGC 5236)

A Supernova Factory:
6 SNe since 1923!
Many core collapse (from massive stars)
~200 SNRs less than 3000 years?

0.25 degree FOV
(note: full moon is 0.5 degree across)

Ground-based image
(photo: Rob Gendler)
How do we find the Supernova Remnants?

5000 ly (1500 pc)
Astronomical Spectra

Rainbow spectrum with dark lines can be displayed as a graph.

Other kinds of light (in this case, ultraviolet) can be displayed in the same way.
Finding Supernova Remnants

Supernova Remnants are heated by explosions (shock waves).

Other emission nebulas are heated by starlight.

Different heating mechanisms cause different emission spectra.

We can use these differences to find SNRs, by taking “narrow band” images and comparing them carefully.
Two SNRs in one small field in M83
M83 SNR Overview


Smaller green circles: WFC3 SNRs (19 nuclear, 41 outer)

60 total SNRs!!
M83 SNR Overview

Larger turquoise circles: 12 previously known SNRs (Blair & Long 2004, ApJS)

Smaller green circles: WFC3 SNRs (19 nuclear, 41 outer, 60 total SNRs) (Estimate ~7 additional WFC3 SNRs would have been seen in IMACS data)
Why Find SNRs in Other Galaxies?
Two Approaches

- Search data set for interesting individual objects that represent rare classes of objects.
  - Core-collapse SNRs (young SNRs from massive stars)
  - Remnants from historical Supernovas in M83

- Use the “ensemble” data set to understand large-scale phenomena in the galaxy as a whole.

- M83 data set is useful for both!
Where are all the “Cas A’s”?

Cas A -- 340 years

If such objects stay visible for ~2000 years, one might have expected 10 - 15 such objects in the single M83 WFC3 field.

(We found ONE!)

Expected signature: a small diameter optical nebula dominated by [O III] and possibly [S II] emission, coincident with a strong X-ray source.
Two Populations of M83 SNRs?

Density: Radiative Age Relationship.

(Slope of -1 expected, but not a bifurcation.)

Lines are offset by a factor of ~4 in density.

What does this mean? Color code dots and look back at the picture (next page).
Spatial Correlation

Yellow: High Density (Nucleus and spiral arms)

Blue: Low Density (More evenly distributed)

Green: Undetermined
Swift Gamma Ray Satellite

- Launched in 2004
- Contains 3 telescopes, that “see” gamma rays, X-rays, and UV-optical light.
- Detection of a burst of gamma rays triggers a sequence of events.
  - Telescope turns quickly and points XRT and UVOT.
  - Pinpoints position of the source.
- Satellite coordinates are radioed to earth and circulated by e-mail within 5 minutes of the event!
  - Ground-based observatories can follow up.
Gamma rays arrive as a “burst” or short duration pulse.
- Two basic varieties: “short” and “long” GRBs.
- Quick follow-up sometimes finds an optical or X-ray afterglow.
- GRBs are due to some very energetic phenomena occurring at great distances from earth, but what?
The GRB - SN Connection

Some “long burst” GRBs have SN counterparts!

Why don’t we always see a GRB with a SN?

Hubble Imaging Follow-ups
(fainter, more distant objects)

Swift UVOT Image

Distant Supernovae

Before Supernova

Hubble Space Telescope • ACS

Before Supernova

NASA and A. Riess (STScI)

Before Supernova

STScl-PRC04-12
Gamma Ray Burst--SN Connection

Supernova Shell

GRB Jets

To Earth
Cas A -- A Possible GRB SN?

High Velocity Jet

Chandra (X-ray)  Hubble (optical)
Supernovae and their remnants (ghosts!) form a fascinating and complex part of the ongoing process of stellar evolution, energizing and enriching the interstellar medium.

Individual objects show a variety of characteristics that do not always track the “standard model.”

Collectively, SNRs can affect star formation and galactic evolution processes.

Some massive star SNe appear to be related to Gamma Ray Bursts.

*Hubble Space Telescope* has played a key role in understanding these objects.

*Hubble* observation of an interaction between a shock wave and an interstellar cloud in Tycho’s SNR (SN 1572).
Questions?