The unshocked ejecta in Cas A and Tycho through low-frequency radio absorption

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Chania, June 2019
The LOw Frequency ARRay

• Interferometer with stations in the Netherlands (24 Core, 14 Remote) and across Europe (12 International)

• 30-90 MHz (LBA); 110-240 MHz (HBA)

LOFAR Superterp, which houses six stations.
1.3 The reverse shock

As already indicated the fast expanding ejecta will rapidly cool adiabatically. As a result the pressure $P$ of the ejecta gas drops fast. For an ideal gas we have:

$$P V = \text{constant} \quad (1.4)$$

with $V$ the volume, and $P^\ast$ and $T^\ast$ the initial pressure and temperature at a radius $R^\ast$.

The fastest moving, outer-most, ejecta will create a shock wave in the CSM/ISM, and as a result a hot shell is created, which has a velocity lower than the ejecta that caused the formation of the shock wave. As a result the freely expanding ejecta inside the shell will collide with the shell. If this collision occurs at supersonic speed then a shock wave will form, which (re)heats the adiabatically cooled ejecta [19]. This shock wave is called the reverse shock (subscript rsh) and to distinguish from the forward moving blast wave, the latter is often referred to as the forward shock (fsh).

The reverse shock (re)heats the ejecta, and makes that in young supernova remnants we detect many X-ray lines from hot metal enriched ejecta (chapter ??). A schematic drawing of a young supernova remnant is shown in Fig. 1.1. It shows that the hot shell consists of two parts, roughly in pressure equilibrium: the outer most shell region consists of ISM/CSM heated by the forward shock, more toward the center is the reverse shock heated ejecta, and inside the reverse shock radius is cold freely expanding ejecta. The boundary between the shock-heated ejecta and CSM/ISM is called the contact discontinuity. As the hot ejecta and shock-heated CSM/ISM are likely to have different densities, Rayleigh-Taylor instabilities are likely to wrinkle this boundary. In addition, clumpiness of the ejecta and/or CSM/ISM are also likely to blur the distinction between hot ejecta and CSM/ISM.

Vink 2020, in prep.
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- Radioactive decay of elements synthesised in the explosion ($^{44}$Ti has $t_{1/2}=60$ years) [Grefenstette+ 16]
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- IR/NIR forbidden lines
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- Radioactive decay of elements synthesised in the explosion ($^{44}\text{Ti}$ has $t_{1/2}=60$ years) [Grefenstette+ 16]
- IR/NIR forbidden lines
- Cold dust mixed with unshocked ejecta
Unshocked ejecta
from low-frequency free-free absorption
[Kassim+ 95]
[Delaney+ 14]

\[ S_\nu = (S_{\nu,\text{front}} + S_{\nu,\text{back}} \exp -\tau_{\nu,\text{int}}) \exp -\tau_{\nu,\text{ISM}} \]
Cas A as seen with the LOFAR LBA and VLA L-band with 10'' resolution. Source size is ~5' [Arias+18]
\[ S_\nu = S_0 \left( \frac{\nu}{\nu_0} \right)^{-\alpha} \left( f + (1 - f)e^{-\tau_{\nu, \text{int}}} \right), \]
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where

\[ \tau_{\nu} = 3.014 \times 10^4 \, Z \, \left( \frac{T}{K} \right)^{-3/2} \left( \frac{\nu}{\text{MHz}} \right)^{-2} \left( \frac{EM}{\text{pc cm}^{-6}} \right) \, g_{ff} \]
\[ S_\nu = S_{1\text{GHz}} \left( \frac{\nu}{1\text{GHz}} \right)^{-0.77} (f + (1 - f)e^{-\tau_{\nu, \text{int}}}) \]

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\]
Mass is a function of a lot of things we don’t know

\[ M = A S l^{1/2} m_p \frac{1}{Z} \sqrt{EM} \]

- Temperature
- Charges (ionisation)
- Composition
- Geometry
Mass is a function of a lot of things we don’t know

\[ M = A S l^{1/2} m_p \frac{1}{Z} \sqrt{EM} \]

- Temperature  100 K (Raymond+18)
- Charges (ionisation)
- Composition
- Geometry
Mass is a function of a lot of things we don’t know

\[ M = A S l^{1/2} m_p \frac{1}{Z} \sqrt{E M} \]

- Temperature \( \text{100 K (Raymond+18)} \)
- Charges (ionisation) \( \text{low ionisation species} \)
  - \( [\text{Si II}] \) (Smith+ 09),
  - \( [\text{O IV}] \) (Isensee+ 10),
  - \( [\text{S III}] \) (Milisavljevic & Fesen 15)
- Composition
- Geometry
Mass is a function of a lot of things we don’t know

\[ M = ASl^{1/2}m_p \frac{1}{Z} \sqrt{EM} \]

- Temperature 100 K (Raymond+18)
- Charges (ionisation) low ionisation species
  - [Si II] (Smith+09),
  - [O IV] (Isensee+10),
  - [S III] (Milisavljevic & Fesen 15)
- Composition Si
  - O (Delaney+14)
  - S, Fe? (Milisavljevic & Fesen 15)
- Geometry
Mass is a function of a lot of things we don’t know

\[ M = A S l^{1/2} m_p \frac{1}{Z} \sqrt{E M} \]

- **Temperature** 100 K (Raymond+18)

- **Charges (ionisation)** low ionisation species
  - [Si II] (Smith+ 09),
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  - [S III] (Milisavljevic & Fesen 15)

- **Composition** Si
  - O (Delaney+ 14)
  - S, Fe? (Milisavljevic & Fesen 15)

- **Geometry**
Geometry

• Thick disk [Delaney+ 10, Isensee+ 10]

• Cavities or bubbles [Milisavljevic & Fesen 15]

• Diffuse emission, with clumps, filaments, arcs [Koo+ 18]
Geometry

- Thick disk [Delaney+ 10, Isee+ 10]
- Cavities or bubbles [Milisavljevic & Fesen 15]
- Diffuse emission, with clumps, filaments, arcs [Koo+ 18]
deep [Fe II]+[Si I] image

Koo+ 18

contours overlaid on our PL deviation map
\[ M = 0.53 \pm 0.10 M_\odot \left( \frac{A}{16} \right) \left( \frac{l}{0.16 \text{pc}} \right)^{1/2} \left( \frac{Z}{3} \right)^{-3/2} \left( \frac{T}{100 \text{ K}} \right)^{3/4} \times \sqrt[4]{\frac{g_{\text{ff}}(T = 100 \text{ K}, Z = 3)}{g_{\text{ff}}(T, Z)}} \]

(previous 3 M⊙ in Arias+ 18)

BUT:
\[ M = 0.53 \pm 0.10 M_\odot \left( \frac{A}{16} \right) \left( \frac{l}{0.16 \text{pc}} \right)^{1/2} \left( \frac{Z}{3} \right)^{-3/2} \left( \frac{T}{100 \text{ K}} \right)^{3/4} \times \sqrt{\frac{g_\text{ff}(T = 100 \text{ K}, Z = 3)}{g_\text{ff}(T, Z)}} \]

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(previous 3 M_\odot in Arias+ 18)

BUT:

Oxygen: 16
Silicon: 28
Sulfur: 32
Iron: 55

estimate can increase by factor of 1.5 or 2
\[ M = 0.53 \pm 0.10 M_\odot \left( \frac{A}{16} \right) \left( \frac{l}{0.16 \text{pc}} \right)^{1/2} \left( \frac{Z}{3} \right)^{-3/2} \left( \frac{T}{100 \text{ K}} \right)^{3/4} \times \sqrt{\frac{g_{\text{ff}}(T = 100 \text{ K}, Z = 3)}{g_{\text{ff}}(T, Z)}} \]

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(previous 3 M_\odot in Arias+ 18)

BUT:

Milisavljevic & Fesen 15 has lines-of-sight that are thinner and thicker can very much alter the estimate
$M = 0.53 \pm 0.10M_{\odot} \left( \frac{A}{16} \right) \left( \frac{l}{0.16 \text{pc}} \right)^{1/2} \left( \frac{Z}{3} \right)^{-3/2} \left( \frac{T}{100 \text{ K}} \right)^{3/4} \times \sqrt{\frac{g_{\text{ff}}(T = 100 \text{ K}, Z = 3)}{g_{\text{ff}}(T, Z)}}$

(previous 3 M⊙ in Arias+ 18)

BUT:
\[ M = 0.53 \pm 0.10 M_\odot \left( \frac{A}{16} \right) \left( \frac{l}{0.16 \text{pc}} \right)^{1/2} \left( \frac{Z}{3} \right)^{-3/2} \left( \frac{T}{100 \text{ K}} \right)^{3/4} \times \sqrt{g_{\text{ff}}(T = 100 \text{ K}, Z = 3)} \]

(previous 3 M\odot in Arias+ 18)

BUT:

Most detected lines of lower ionisations

[Si II] (Smith+ 09), [Si I] (Koo+ 18), [O IV] (Isensee+ 10), [S III] (Milisavljevic & Fesen 15)

neutrals not factored
\[ M = 0.53 \pm 0.10 M_\odot \left( \frac{A}{16} \right) \left( \frac{l}{0.16 \text{pc}} \right)^{1/2} \left( \frac{Z}{3} \right)^{-3/2} \left( \frac{T}{100 \text{ K}} \right)^{3/4} \sqrt{\frac{g_{\text{ff}}(T = 100 \text{ K}, Z = 3)}{g_{\text{ff}}(T, Z)}} \]

(previous 3 M_\odot in Arias+ 18)

BUT:

plus, effect of clumping
(Arias+ 18)
\[ M = 0.53 \pm 0.10 M_\odot \left( \frac{A}{16} \right) \left( \frac{l}{0.16\,\text{pc}} \right)^{1/2} \left( \frac{Z}{3} \right)^{-3/2} \left( \frac{T}{100\,\text{K}} \right)^{3/4} \times \sqrt{\frac{g_{\text{ff}}(T = 100\,\text{K}, Z = 3)}{g_{\text{ff}}(T, Z)}} \]
This method allows us to locate the rim of absorbing material (i.e., the reverse shock). More than providing a firm estimate of the mass, it is a probe into the conditions in the unshocked ejecta.
Tycho’s SNR in the LOFAR HBA at 143 MHz, 9.5” resolution.
Tycho as seen with the LOFAR LBA (48.3 MHz and 67.0 MHz) with 30'' resolution. Source size is ~8'  Arias+18
LOFAR HBA
143 MHz

VLA 1.4 GHz
Williams+ 16
Flux densities measured with the LOFAR HBA and LBA match literature values of this well-known source (3C10)
\[ S_\nu = S_0 \left( \frac{\nu}{\nu_0} \right)^{-\alpha} \left( f + (1 - f)e^{-\tau_{\nu,\text{int}}} \right)e^{-\tau_{\nu,\text{ISM}}} \]
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S_{\nu} = S_0 \left( \frac{\nu}{\nu_0} \right)^{-\alpha} \left( f + (1 - f)e^{-\tau_{\nu,\text{int}}} \right)e^{-\tau_{\nu,\text{ISM}}}
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To estimate mass from the measured absorption we need:

- degree of ionisation and composition
- temperature
- geometry of the material

Tycho was a Type Ia explosion: originally 1.4 M☉

This plot corresponds to $EM=103 \text{ pc cm}^{-6}$ in the region within the reverse shock, which is very high
To estimate mass from the measured absorption we need:

- degree of ionisation and composition \( \text{Fe} \)
- temperature
- geometry of the material

Tycho was a Type Ia explosion: originally 1.4 \( M_\odot \)

This plot corresponds to \( \text{EM} = 103 \text{ pc cm}^{-6} \) in the region within the reverse shock, which is very high.
• To estimate mass from the measured absorption we need:

• degree of ionisation and composition \( \text{Fe} \)

100 K — 91 M\( \odot \)
10 K — 25 M\( \odot \)

• temperature 2.7 K— 19 M\( \odot \)

• geometry of the material

• Tycho was a Type Ia explosion: originally 1.4 M\( \odot \)

This plot corresponds to \( \text{EM} = 103 \text{ pc cm}^{-6} \) in the region within the reverse shock, which is very high
- To estimate mass from the measured absorption we need:
  - degree of ionisation and composition Fe
  - temperature 100 K — 91 M⊙
  - temperature 10 K — 25 M⊙
  - temperature 2.7 K — 19 M⊙
  - geometry of the material
- Tycho was a Type Ia explosion: originally 1.4 M⊙

This plot corresponds to $EM = 103 \text{ pc cm}^{-6}$ in the region within the reverse shock, which is very high
To estimate mass from the measured absorption we need:

- degree of ionisation and composition
- temperature
- geometry of the material

Tycho was a Type Ia explosion: originally 1.4 $M_\odot$

This plot corresponds to $EM=103$ pc cm$^{-6}$ in the region within the reverse shock, which is very high
PRELIMINARY

Is it possible that ejecta have a very different structure? [Fe-rich knot, Yamaguchi+ 17] Foamy?

Can Fe be very highly ionised?

Might Tycho be ionising the medium around it?

Mass in unshocked ejecta from observed FS, RS, for an ejecta density profile with a PL distribution and a flat distribution in the core
Thanks!
\[ X(\nu, Z, T) = Z \left( \frac{T}{K} \right)^{-3/2} \left( \frac{EM}{\text{pc cm}^{-6}} \right) \left( \frac{g_{ff}(T, Z)}{g_{ff}(T = 100 \, \text{K}, Z = 3)} \right) \]
\[ X(\nu, Z, T) = Z \left( \frac{T}{K} \right)^{-3/2} \left( \frac{EM}{\text{pc cm}^{-6}} \right) \left( \frac{g_{ff}(T, Z)}{g_{ff}(T = 100 \text{ K}, Z = 3)} \right) \]
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\[ EM = n_e^2 l \]
\[ X(\nu, Z, T) = Z \left( \frac{T}{K} \right)^{-3/2} \left( \frac{EM}{\text{pc cm}^{-6}} \right) \left( \frac{g_{ff}(T, Z)}{g_{ff}(T = 100 K, Z = 3)} \right) \]

\[ EM = r_{e}^{2} l \]
\[ X(\nu, Z, T) = Z \left( \frac{T}{K} \right)^{-3/2} \left( \frac{EM}{\text{pc cm}^{-6}} \right) \left( \frac{g_{ff}(T, Z)}{g_{ff}(T = 100 \text{ K}, Z = 3)} \right) \]

\[ EM = n_{e}^{2}l \]

\[ M_{\text{unsh}} = \rho V = \rho Sl \]
\[ X(\nu, Z, T) = Z \left( \frac{T}{K} \right)^{-3/2} \left( \frac{EM}{\text{pc cm}^{-6}} \right) \left( \frac{g_{ff}(T, Z)}{g_{ff}(T = 100 \text{ K}, Z = 3)} \right) \]

\[ EM = n_e^2 l \]

\[ M_{\text{unsh}} = \rho V = \rho Sl \]

\[ \rho_{\text{ions}} = n_i \times \text{mass}_{\text{ions}} = \frac{n_e}{Z} \times Am_p \]
\[ X(\nu, Z, T) = Z \left( \frac{T}{K} \right)^{-3/2} \left( \frac{EM}{\text{pc cm}^{-6}} \right) \left( \frac{g_{ff}(T, Z)}{g_{ff}(T = 100 \text{ K}, Z = 3)} \right) \]

\[ EM = n_e^2 l \]

\[ M_{\text{unsh}} = \rho V = \rho S l \]

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\[ \rho_{\text{ions}} = n_i \times \text{mass}_{\text{ions}} = \frac{n_e}{Z} \times Am_p \]

\[ M = ASl^{1/2} m_p \frac{1}{Z} \sqrt{EM} \]