Eta Carinae and the Pre-Supernova Circumstellar Material of Massive Stars

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The sub-arcsecond dusty environment of Eta Carinae

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- Highest resolution near-IR images of Eta Car obtained so far.
- MIDI: Differences in dust composition on very small spatial scales.
MASS LOSS & STELLAR EVOLUTION
(see review Smith 2014, ARAA, 52, 487)
and remember Jose Groh’s talk on monday
Thermal-IR
Magellan/MIRAC3
8.8 µm
12.5 µm
18.0 µm
VLT AO imaging
NAOS/CONICA

VLT images made by Olivier (Chesneau + 2005)
Gemini South/Phoenix
R=60,000
(Smith 2006)

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2.122 \mu m \text{ H}_2 1-0 S(1)
VLT AO imaging
NAOS/CONICA

VLT images made by Olivier (Chesneau + 2005)

Gemini South/Phoenix
R=60,000
(Smith 2006)

2.122 µm H$_2$ 1-0 S(1)
1.644 µm [Fe II]
Olivier's Butterfly Nebula is the equator of the Homunculus seen in hot dust and H2.
Episodic dust formation in Eta Car:

Eccentric colliding-wind binary with X-rays and hot dust at periastron.
Episodic dust formation in Eta Car:

Peaks in near-IR light curve have SED of hot dust at 1500-1700 K.

Not free-free or reddened starlight.
Episodic dust formation in Eta Car:

Dust temp is too hot for silicates.

Probably corundum (Al$_2$O$_3$; alumina), since gas around Eta Car is very C-poor. Condenses at 1700 K.

Similar to dust formation in WC+O binaries (Tony Moffat’s talk), but probably not C rich.
The sub-arcsecond dusty environment of Eta Carinae

O. Chesneau\textsuperscript{1}, M. Min\textsuperscript{2}, T. Herbst\textsuperscript{1}, L. B. F. M. Waters\textsuperscript{2}, D. J. Hillier\textsuperscript{3}, Ch. Leinert\textsuperscript{1}, A. de Koter\textsuperscript{2}, I. Pascucci\textsuperscript{1}, W. Jaffe\textsuperscript{4}, R. Köhler\textsuperscript{1}, C. Alvarez\textsuperscript{1}, R. van Boekel\textsuperscript{2}, W. Brandner\textsuperscript{1}, U. Graser\textsuperscript{1}, A. M. Lagrange\textsuperscript{5}, R. Lenzen\textsuperscript{1}, S. Morel\textsuperscript{6}, and M. Schöller\textsuperscript{6}

- Silicates are in Homunculus walls
- Corundum from new dust formed in wind-wind collisions fills the central region
DUST TEMPERATURES
(from color temp in images)

DUST MASS (from the ISO spectrum)

\[
\frac{100 \times M(\text{dust})}{M_\odot} = \begin{array}{ccc}
400K & 200K & 140K \\
0.02 \ M_\odot & 1.5 \ M_\odot & 11 \ M_\odot
\end{array}
\]

Total = 12.5 \ M_\odot

Previous estimates from \( \lambda = 2-12 \ \mu m \) typically gave 2-3 \( M_\odot \).

Higher mass comes from cool dust emitting at \( \lambda > 12 \ \mu m \).  

Cloudy models of gas excitation in nebula suggest 17 \( M_\odot \) or more.

Total IR luminosity \( 4.3 \times 10^6 \ L_\odot \)

Smith et al. 2003

Smith & Ferland 2007
Ejected mass = 10-15 $M_{\odot}$

$KE = 10^{49.6} - 10^{50}$ erg

$E_{rad} = 10^{49.7}$ erg

Range of Ejecta Speed = 40 - 650 km/s

Follows a Hubble law

$\frac{KE}{E_{rad}} \approx 1$

Wind or Explosion?
In circumstellar shells around LBVs, a mass of $\sim 10 \, M_\odot$ is typical for $L_\ast > 10^6 \, L_\odot$.

Less massive shells also seen, indicating a **variety** of outburst energy and mass.

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Efficient conversion of KE → Light

We can observe $V_{SN}$, $V_w$ and $L$, and thus constrain CSM mass.

SNe II\textsubscript{n} require several $M_\odot$ of CSM ejected only a few years before core collapse.
Diversity of SN II\textsc{in} luminosity: Increasing CSM mass

A range of circumstellar shell mass provides a huge observed range of luminosity for SNe II\textsc{in}.

- Very luminous SNe II\textsc{in} (rare) require massive LBV-like eruptions before core collapse.
  - Observed CSM expansion speeds of 100-600 km/s
- Lower luminosity (most common II\textsc{in}) can be extreme red supergiants or LBVs.
  - Observed CSM expansion speeds of 20-500 km/s

Efficient conversion of KE \(\rightarrow\) Light

\[
\text{Absolute magnitude (R or unfiltered)}
\]

\[
\text{Time (Days)}
\]
Very luminous SNe IIn require high mass of CSM
- some require >10 $M_\odot$ ejected in decade before core collapse.

5 direct detections of SN progenitors (or host cluster)
- SN 2005gl $M_0 \approx 50-60$ $M_\odot$ (Gal-Yam & Leonard 2009)
- SN 1961V $M_0 \approx 100$ $M_\odot$ (Smith et al. 2011, Kochanek 2011)
- SN 2010jl $M_0 > 30$ $M_\odot$ (Smith et al. 2011)
- SN 2009ip $M_0 \approx 50-80$ $M_\odot$ (Smith+2010, Mauerhan+13)
- SNhunt275 – preSN eruptions (still going)

This was forbidden in standard single star models

But caution: LBVs are bright, easy to detect
If LBVs explode, where do we get WR stars and SNe Ibc?

Also, SN Ibc ejecta masses are too low. Most must come from binaries (Dessart et al. 2012).
If LBVs explode, where do we get WR stars and SNe Ibc?

LBV (luminous blue variables) Type IIn

type

Wolf-Rayet Ib/c

B...
RY Scuti: eclipsing massive binary system in transition to WR+O via RLOF.

A more massive analog of β Lyrae (J. Nemravova talk)

Two separate ejections.

Age = 130 yr

1881 ± 4

1754 ± 32

Age = 255 yr

HST/WFPC2 Hα

Keck/NIRC2-AO Lp

Smith et al. (2011)

[See poster outside by Gehrz, Smith, & Shenoi]

Mass donor: Will be a WR

Mass gainer: Will be a rapidly rotating O star, B[e], or LBV?

RY Scuti

ϕ = 0.25

11 day period

Primary
O9.7 Ibpe
8 Msun
RLOF

Secondary
B0.5 I
30 Msun
opaque accretion torus

Size of major axis (arcsec)

Year

1800 1850 1900 1950 2000

Keck Lp

HST Hα + VLA

HST Hα
Slow outflow $V \approx 20$ km/s

Even though wind speeds are several $10^2$ km/s

Equatorial mass loss reminiscent of low-mass symbiotics (talk by Shazrene M.)
The yellow hypergiant HR 5171 A: Resolving a massive interacting binary in the common envelope phase

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- 1304d eclipsing contact binary
- Resolved 2 stars with VLTI (1\textsuperscript{st} ever)
- Undergoing RLOF
- May evolve to B[e] or LBV / WR
We require the ejection of a very slow & dense equatorial ring. How?

1. MERGER. Morris & Podsiadlowski 2007, 2008, etc.
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1. MERGER. Morris & Podsiadlowski 2007, 2008, etc.

Some problems/objections:

• Predicts filled polar caps and empty equator. Observations suggest opposite.

By now, these polar caps would have been hit 5-10 yrs ago by the fastest ejecta going 35,000 km/s.
We require the ejection of a very slow & dense equatorial ring. How?

1. MERGER. Morris & Podsiadlowski 2007, 2008, etc.

Some problems/objections:

• Predicts filled polar caps and empty equator. Observations suggest opposite.

• For successful merger, equatorial mass shed is at least 4-5 $M_\odot$. This seems high for SN1987A’s ring, and is too high for SBW1 ($M<1 M_\odot$).

The equatorial outflow occurs as the envelope loses angular momentum during the blue loop. The total mass lost can be estimated from angular momentum conservation

$$M_{ER} = \frac{\Delta L}{\sqrt{GM_\ast R_\ast (1 - \Gamma)}} \sim 4 M_\odot$$

if the mass is lost near critical rotation (as suggested by the low expansion velocity of the ring of around $10.3 \text{ km s}^{-1}$). Here $\Delta L$ is the excess angular momentum that needs to be lost, i.e. is the difference between the post-merger angular momentum in the envelope and the maximum angular momentum for a stable blue supergiant ($\sim 4 \times 10^{54} \text{ erg s}$). We assume an Eddington factor of $\Gamma = 0.4$ and that the envelope must lose $\sim 6 \times 10^{54} \text{ erg s}$ at a radius of roughly 6000 $R_\odot$. This is likely to be a lower limit unless magnetic processes in the excretion disk can increase
We require the ejection of a very slow & dense equatorial ring. How?

1. MERGER. Morris & Podsiadlowski 2007, 2008, etc.

Some problems/objections:

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• For successful merger, equatorial mass shed is at least 4-5 $M_{\odot}$. This seems high for SN1987A’s ring, and is too high for SBW1 ($M<1 M_{\odot}$).

• The resulting BSG merger product is rotating at critical rotation, and takes several Myr to spin down with the low inferred wind mass-loss rate. Age of equatorial ring is only 1-2e4 yr.
Mergers produce rapid rotators

- Mass transfer with a post-MS donor results in a rapidly rotating secondary.
- Mass transfer with a post-MS donor results in a post-MS merger.
- Mass transfer with a MS donor results in a rapidly rotating secondary.

Rotational velocity $v_{\text{rot}}$ vs. time (Myr) shown for primary, secondary, and merger events.

Keplerian velocity $v_K$ also shown for primary and secondary components.

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de Mink et al. (2013)
Sher 25: pulsating but apparently alone

William D. Taylor, Christopher J. Evans, Sergio Simón-Díaz, Hugues Sana, Norbert Langer, Nathan Smith and Stephen J. Smartt

FEROS/ESO2.2m – echelle spectra

SBW1:

Lack of radial velocity variation rules out a close massive companion. Might allow low-mass (<1 Msun) wide (P= yrs) companion or highly eccentric orbit.

Also, narrow lines indicate a SLOW equatorial rotation speed of only 41 km/s.

(In fact, all 3 are relatively slow rotators)
SBW1:

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Also, narrow lines indicate a SLOW equatorial rotation speed of only 41 km/s.

(In fact, all 3 are relatively slow rotators)
We require the ejection of a very slow & dense equatorial ring. How?

2. RSG – BSG contraction and spin up.

3. RLOF event in wider binary. Short duration (few 1000 yr) mass-transfer phase. Produces very slow equatorial outflow Through L2.

Is the (low-mass?) companion still there?

Why did this happen right before SN?

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**Langer et al. (1998)**

Figure 3. Equatorial rotation velocity as a function of time (solid line) of a model 12 $M_\odot$ rotating star during the transition from the red-supergiant branch to the blue-supergiant stage during core helium burning ($t = 0$ is arbitrary). It is compared to the Keplerian (dashed line) and decoupled (dash-dotted line) rotation velocities. The critical (dotted line) is reached when the star is close to the L1 point.
If LBVs explode, where do we get WR stars and SNe Ibc?

Wolf-Rayet

II-P 48.2%

II-L 6.4%

Ic 14.9%

Ib 7.1%

Ibc-pcc 4.9%

IIb 10.6%

II In 8.8%

Core-Collapse SN Fractions

Smith et al. (2011) MNRAS, 412, 1522

Also, SN Ibc ejecta masses are too low. Most must come from binaries (Dessart et al. 2012).

Binary-star mass-transfer

(ROCHE LOBE OVERFLOW)

Only 3 massive star binaries caught in brief RLOF phase with spatially resolved CSM.

Paczynski et al. 67; Podsiadlowski et al. 92
WHICH KNOWN H-RICH STARS HAVE HIGH-ENOUGH MASS-LOSS RATES TO BE Type IIIn SUPERNOVAE?

\[ M = 2Lv_w/(v_{SN})^3 \]

For Type IIIn SN progenitors:

\[ \langle M \rangle \]

Minimum M needed to be observed as a Type IIIn for:

- \( L = 10^9 L_\odot \)
- \( v_{SN} = 5000 \text{ km/s} \)
- \( v_{SN} = 10^4 \text{ km/s} \)

RY Scuti: eclipsing massive binary system in transition to WR+O via RLOF.
(Smith et al. 2011, arXiv:1105.2329)

Repeated equatorial ejections every 120 years (cyclical?).

WHY?

RLOF...

Accretion onto mass gainer companion:

Overluminous
Out of thermal equilibrium
Critical rotation

(LBVss, Be stars, B[e]sg...?)

What about the mass gainer’s SN?
Weaker polarization (lower asymmetry) during broad-line SN photosphere phase (2012a and end of 2012b).

Stronger polarization (high asymmetry) in CSM-interaction dominated phase (2012b peak).

Two components are roughly orthogonal in PA.
PROPERTIES OF SN2006gy’s CSM

A Massive LBV-like Shell: Clues from Spectral Evolution

Time evolution of Luminosity

• High CSM density required to drain KE...

\[ L = \frac{1}{2} 4\pi R^2 \rho V_{\text{shock}}^3 \]

• Cumulative swept-up CSM mass:
\[ \geq 18 \, M_{\odot} \]

\[ E_{\text{rad}} = 2.5 \times 10^{51} \text{ erg} \quad E_K = 3 \times 10^{51} \text{ erg} \]
PROPERTIES OF SN2006gy’s CSM

A Massive LBV-like Shell: Clues from Spectral Evolution

Time evolution of narrow H\textalpha


• Narrow absorption gets weaker... 
  ...running out of CSM?
• Narrow absorption gets broader... 
  ...faster CSM at larger radii?
PROPERTIES OF SN2006gy’s CSM

A Massive LBV-like Shell: 
Clues from Spectral Evolution

Time evolution of narrow Hα 

- Narrow absorption gets weaker... 
  ...running out of CSM?
- Narrow absorption gets broader... 
  ...faster CSM at larger radii?

Hubble Flow at 150-500 km/s 
Suggests $\geq 10^{49}$ erg ejection 
~8 yr before SN (fall 1998)
Comparing the CSM of Eta Carinae and SN 2006gy:

**Both had multiple massive shell ejections.**

- **Inner massive shell**, H-rich, $M \sim 10-20\, M_\odot$
éjected at 100-600 km/s, Hubble law
- **Outer massive shell**, $R \sim 1\, \text{ly}$
éjected ~1000-2000 yr earlier

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*Smith et al. 2005*
Light Echoes

Ela Carinae

2003 March 10 (A)

Diffim C-A

2008 May 10 (B)

Diffim C-B

2011 February 6 (C)

C-A Diffim Zoom

31x159

Smith & Frew (2010)

Light Echoes

B-V=0.7–1.2

(a Cen, a Boo)

Scaled F, + constant

Rest Wavelength (Å)

1850

1860

SN 2009ip

SN 1997bs

UGC 2773 OT1

CG 1C

CG 1B

CG 1A

(NII)

Hα

SN 2009ip

SN 1997bs

UGC 2773 OT1

CG 1C

CG 1B

CG 1A
Can dust form in strong shocks?

WC+O Colliding-wind binaries do it. (they are C-rich)

**persistent dust producers**  
(a.k.a. “Pinwheels”)

**episodic dust producers**  
(at periastron like WR140)

Tuthill et al., Monnier et al.
END FATES of MASSIVE STARS:
What type of supernova from which type of star?

- Type II-P
- Type II-L
- Type IIb
- Type Ib
- Type Ic (GRB)

Single-star mass-loss
(STELLAR WINDS and ERUPTIONS)

Binary-star mass-transfer
(ROCHE LOBE OVERFLOW)

Image courtesy M. Modjaz

Heger et al.
Woosley et al.
Maeder & Meynet

Paczynski et al. 67; Podsiadlowski et al. 92

Mass loser
Roche lobe of companion
Mass gainer
Rotational
Mass-transfer stream
Accretion disk
Supernovae: SN types & initial mass.

SN subtype fractions from the LOSS (Li et al. 2011)

Smith et al. (2011)
MNRAS, 412, 1522

Large galaxies, roughly $Z\odot$
Sana et al. 2012, de Mink et al. 2013 (see also Kiminki et al. 2007, 2014; Kobulnicky & Fryer, etc.):

- Binary interaction must dominate the evolution of massive stars
- Roughly 2/3 of massive stars will interact & exchange mass or merge
**CONSTRAINTS FROM SUPERNOVA PROGENITOR STARS**

**Type II-P**
- RSGs with initial mass $8.5 - 20 M_\odot$ ($\sim 12$)
- Most common.
- Single stars (or wide binaries) of low-ish mass.

**Type Ibc**
- Zero detections, but probably mostly binary (10-15 upper limit)

**Type IIb**
- $13-18 M_\odot$ binary (3)
- Might favor locations in clusters. Could be 8-100 $M_\odot$

**Type II-L**
- $18-25 M_\odot$ (2)
- Like II-P, but a little more massive (?)

**Type II-n**
- $>30-100 M_\odot$ (4)
- LBV-like. Some very massive stars, but weird & poorly understood.

**Also:** SN ejecta masses of SNe Ibc & IIb are small (Dessart et al.; Haschinger et al.)