Symbiotic Stars

Rodolfo Angeloni
**In short**

**Symbiotic stars** are long-period interacting binaries in which an evolved giant transfers material to a hot and luminous companion surrounded by an ionized nebula.
**In short**

The **hot component** of a symbiotic system is (generally) a hot white dwarf.

The **evolved giant** can be either a normal red giant (**S-type** symbiotic) or a Mira usually surrounded by a warm dust shell (**D-type** symbiotic).

**Orbital period**

- **S-types** ~1-15 years
- **D-types** >20 years
In short

Webster & Allen 1975, Allen 1982
In short

More than 200 SSs known
Belczyński et al. (2000)

- 81% S type
- 15% D type
- 4% D' type
**In short**

Open questions: the symbiotic population

**Present sample**
- 173 + 26 suspected
  (Belczyński et al. 2000)

**Predicted total number**
- $3 \times 10^3$ (Allen 1984)
- $3 \times 10^5$ (Munari & Renzini 1992)
- $3 \times 10^4$ (Kenyon et al. 1993)
- $4 \times 10^5$ (Magrini et al. 2003)

...but see e.g. *IPHAS & Symbiotic Stars*
Corradi et al., 2008 – 2011

10/03/2017

Variable Stars - Lecture V - OAC Córdoba
In short

Symbiotic Stars

as unique astrophysical laboratories

- nova-like thermonuclear outbursts (e.g. Munari et al. 1997; Shore et al. 2011)
- colliding-wind processes (e.g. Mürset et al. 1995; Kenny & Taylor 2005, 2007)
- formation and collimation of jets (e.g. Tomov 2003; Angeloni et al. 2011)
- bipolar PNe (e.g. Corradi 2003; Phillips & Ramos-Larios 2008)
- variable X-ray emission (e.g. Mukai et al. 2007; Masetti et al. 2011)
- non-negligible subclass of X-ray binaries (Nespoli et al. 2009; Eze 2011)
- effect of binary evolution on AGB component (e.g. Marigo & Girardi 2007)
- real-time laboratory for dust formation/destruction (e.g. Angeloni et al. 2007a, 2010)
- progenitors of Supernovae Ia (e.g. Munari & Renzini 1992, Hachisu et al. 1999, Lü et al. 2009)
In short

Resolving a symbiotic star into its emitting components

They dominate the spectral energy distribution (SED) at specific wavelengths

“... this is both a blessing and a curse: a well-defined observational program may probe a particular component of a symbiotic system, but knowledge of the complete SED is required to make progress on understanding the system as a whole.”

S. Kenyon (1986)
OUTLINE

- An Historical Perspective
- The Symbiotic Phenomenon
- Classification Criteria
- Symbiotic Outbursts
- Symbiotic Emitting Components

  hot star
  cool star
  nebula (+ outflows)
An historical perspective

“... anomalous combination in a single spectrum of features that ordinarily occur near opposite ends of the sequence of stellar temperatures.”

Merrill & Humason (1932)

“... puzzling evidence of “bright emission lines requiring an excitation far above that which a low temperature photosphere appears able to supply.”

Merrill (1944)

“Stars with combination spectra”

Group III of Merrill’s classification scheme (Merrill 1944)

... a qualitative binary model where “the orbital motion and the proximity of a nebular shell may account for the irregular light variations commonly observed, as well as for the complex changes in the bright line spectrum.”

Berman (1932)

“... to understand why a high-excitation line of ionized helium should appear along with the spectrum of a molecule [e.g., TiO] that is dissociated at a relatively low temperature?”

Merrill & Humason (1932)
1. Introduction

The symbiotic nova RR Telescopii displays a rich emission line spectrum, ranging from N i to [Ni viii]. We present a list of 811 measured lines, with their suggested identifications and absolute intensities, covering a wavelength range from 3180 Å to 9455 Å. Comparing results with those of previous studies indicates that the RR Tel system is advancing towards higher degrees of ionization. RR Tel has been the subject of many extensive spectroscopic investigations. (e.g., Aller et al. 1973) due to the great wealth of lines emitted since its outburst in 1944. Thieberger (1977) has compiled the observations of RR Tel from its outburst until the mid 1970s, and cites most relevant references.

2. Line Identifications and Intensities

The methods employed in identifying the many emission lines are described in McKenna et al. (1997) and Crawford et al. (1999). Crawford et al. (1999) have tentatively identified O vi emission at λ3811.36 and 3834.24 Å; these features are blended with stronger O iii lines. There is further evidence of O vi emission with extremely broadened features at λλ6585 and 7082 Å, which have been identified by Espey et al. (1995) as the Ramond-scattered ultraviolet O vi λλ1032 and 1038 Å resonance lines (Schmid 1989). These lines have split profiles, probably due to relative gas motions in the red giant's wind.

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RR Tel

22.33/04/95

ES0 1.5 m + B&C

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RR Tel

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It is inadvisable to accept any hypothesis without reserve
Merrill 1944

- Cool star + hot envelope?
- Hot star + cool envelope?
- Binary star?

“It is inadvisable to accept any hypothesis without reserve”
Merrill 1944
When space-based missions such as *IUE* in the UV and *IRAS* in the IR started to open new wavelength ranges, it became clear that the standard view of SSs was far too simplistic.

![Graph showing spectral lines](image)

*The hot star becomes visible in the UV!*

- Cool star + hot envelope?
- Hot star + cool envelope?
- Binary star!

From Kenyon 1990
The “symbiotic phenomenon”

I. a composite stellar spectrum with apparently conflicting features;

II. ...

from Munari & Zwitter 2002

from Magrini et al. 2005
The "symbiotic phenomenon"

I. a composite stellar spectrum with apparently conflicting features;

II. (irregular) photometric and spectroscopic variability

Variability distinguishes SSs from both normal cool stars and gaseous nebulae.
The “symbiotic phenomenon”

I. a composite stellar spectrum with apparently conflicting features;
II. (irregular) photometric and spectroscopic variability

Origin of the variability

- Intrinsic
- Ellipsoidal
- Outburst
- Warming/reflection
- Eclipses
- Reprocessing of circumstellar gas
- Flickering
- Dust obscuration episodes
- ...

AX per
The large variety of phenomenology displayed by SSs is hard to include in a coherent scheme.

Do they really represent a homogeneous group of stars or are rather a sort of dustbin of badly understood stellar objects?
Classification criteria

RR Tel

Classification criteria:

- Presence of the absorption features of a late-type giant; in practice, these include (amongst others) TiO, H$_2$O, CO, CN and VO bands, as well as CaI, CaII, FeI and NaI absorption lines;

- Presence of strong emission lines of HI and HeI and either emission lines of ions with an ionization potential of at least 35 eV (e.g. [OIII]), or an A- or F-type continuum with additional shell absorption lines from HI, HeI, and singly-ionized metals;

- The presence of the $\lambda$6825 Å emission feature, even if no features of the cool star (e.g. TiO bands) are found.

Symbiotics are a class of variable stars spectroscopically defined!
Based on their activity, all symbiotic stars can be split into two subclasses:

**Classical Symbiotic Stars**
(prototype: Z And)

**Symbiotic Novae**
- slow
- recurrent
Classical Symbiotic Star

The typical (quiescent) hot components of classical symbiotics appear to be quite hot (~10^5 K) and luminous (~100⁻10 000 L☉), and they overlap in the same region in the HR diagram as central stars of planetary nebulae.
“All the objects, including pure symbiotic Miras never classified as PNe, lie within the locus of genuine Pne” (from Schmeja & Kimeswenger 2001).
Classical Symbiotic Star

They show occasional 1–3 mag optical/UV outbursts on timescales from months to years, when the hot component luminosity remains roughly constant whereas its effective temperature varies from $\sim 10^5$ to $\sim 10^4$ K.

Unstable disc-accretion onto H-shell burning white dwarf?

No quantitative models, yet.
**Symbiotic Novae**

= thermonuclear novae

The total radiation output of a symbiotic nova outburst is of the order of $10^{47}$ erg! From all eruptive stellar events only SN are more energetic than symbiotic novae.

**Symbiotic Novae**

- **SLOW**
  - 9 objects
  - Outbursts can go on for decades

- **RECURRENT**
  - 4 objects (all S-types)
  - Outburst last several days, and recurrence times are of order of several years

The differences in outburst behavior seem to reflect different white dwarf masses (higher WD masses in SyRNe)
Symbiotic Novae
slow vs. recurrent

Optical and UV light curves of the slow symbiotic nova PU Vul (left) and the AAVSO optical light curve of the symbiotic recurrent nova RS Oph (right) covering identical time intervals (from Kato et al. 2012).

The differences in outburst behavior seem to reflect different white dwarf masses (higher WD masses in SyRNe).
The differences in outburst behavior seem to reflect different white dwarf masses (higher WD masses in SyRNe)

Fig. 6. The plateau lifetime–luminosity relationship for symbiotic novae. To associate mass and luminosity on the top axis of the figure, the mass-luminosity relationship for the plateau phase from [11] was adopted.
Symbiotic Novae
the “strange case” of V407 Cyg

The most recent symbiotic nova V407 Cyg (2010) shares characteristics of both groups: it has a Mira companion but its very fast outburst development is typical for the SyRNe.
Symbiotic Novae: the “strange case” of V407 Cyg

The most recent symbiotic nova V407 Cyg (2010) shares characteristics of both groups: it has a Mira companion but its very fast outburst development is typical for the SyRNe.

Figure 1. Photometric evolution of V407 Cyg over the last 16 yr, or seven Mira’s pulsation cycles. The dashed line is hand drawn to provide a guide through the long-lasting active phase that peaked in 1998. The right-hand panels provide a zoom over the 2010 outburst.
Symbiotic Novae
the “strange case” of V407 Cyg

V407 Cyg is exceptional among D-type systems since it has the longest pulsation period among the symbiotic Miras and the only one which is Li-rich (Tatarnikova et al. 2003).

- initial mass of the current Mira of 4-8 $M_{\text{Sun}}$
- very strong wind ($10^{-5} M_{\text{Sun}}$/year)

¡Higher accretion rates!
Symbiotic Novae
the “strange case” of V407 Cyg

The imprint of a symbiotic binary progenitor on the properties of Kepler’s supernova remnant

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ABSTRACT

We present a model for the type Ia supernova remnant (SNR) of SN 1604, also known as Kepler’s SNR. We find that its main features can be explained by a progenitor model of a symbiotic binary consisting of a white dwarf and an AGB donor star with an initial mass of 4–5 $M_\odot$. The slow, nitrogen-rich wind emanating from the donor star has partially been accreted by the white dwarf, but has also created a circumstellar bubble. On the basis of observational evidence, we assume that the system moves with a velocity of 250 km s$^{-1}$. Owing to the spatial velocity, the interaction between the wind and the interstellar medium has resulted in the formation of a bow shock, which can explain the presence of a one-sided, nitrogen-rich shell. We present two-dimensional hydrodynamical simulations of both the shell formation and the SNR evolution. The SNR simulations show good agreement with the observed kinematic and morphological properties of Kepler’s SNR. In particular, the model reproduces the observed expansion parameters ($m = V(R/t))$ of $m = 0.35$ in the north and $m = 0.6$ in the south of Kepler’s SNR. We discuss the variations among our hydrodynamical simulations in light of the observations, and show that part of the blast wave may have completely traversed through the one-sided shell. The simulations suggest a distance to Kepler’s SNR of 6 kpc, or otherwise imply that SN 1604 was a sub-energetic type Ia explosion. Finally, we discuss the possible implications of our model for type Ia supernovae and their remnants in general.

Key words. ISM: supernova remnants – hydrodynamics – binaries: symbiotic – supernovae: individual: SN1604
Cassiopeia A Supernova Remnant

NASA / JPL-Caltech / O. Krause (Steward Observatory)

spc2005-14c

Spitzer Space Telescope • MIPS
Hubble Space Telescope • ACS
Chandra X-Ray Observatory
Symbiotic Stars & other binary accretors

“A hierarchy of time-scales, sizes, and accretion rates...”

<table>
<thead>
<tr>
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<th>Cataclysmic Variables</th>
<th>Supersoft Sources</th>
<th>Symbiotics</th>
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<td>Hours</td>
<td>Hours – Days</td>
<td>Years</td>
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<td>Mass Transfer Mechanism:</td>
<td>Stable RLOF$^a$</td>
<td>Unstable RLOF</td>
<td>Wind or RLOF</td>
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<td>$\dot{M}<em>{WD}(M</em>{\odot} \text{ yr}^{-1})^b$:</td>
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<td>$10^{-8}–10^{-6}$</td>
<td>$10^{-9}–10^{-5}$</td>
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<td>$\approx 190$</td>
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<td>?</td>
<td>Yes</td>
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<td>TNR$^a$ &amp; DI$^a$</td>
<td>Cause?</td>
<td>Cause?</td>
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<tr>
<td>Disc:</td>
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<td>Yes</td>
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<tr>
<td>Steady Nuclear Burning:</td>
<td>No</td>
<td>Yes</td>
<td>Some</td>
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<tr>
<td>Flickering:</td>
<td>Yes</td>
<td>Some</td>
<td>Some</td>
</tr>
</tbody>
</table>

$^a$ RLOF=Roche lobe overflow; TNR=thermonuclear runaway; DI=disc instability.

$^b$ $\dot{M}_{WD}$ is the time-averaged accretion rate on to the white dwarf.

(from Sokoloski et al. 2001)
The hot component

FLICKERING can help in better understanding the nature of the WD accretors in SSs

✓ Flickering is the phenomenon of rapid, apparently random variability in the optical emission of accreting binary stars.

✓ It occurs on many time-scales, from rapid fluctuations lasting a few seconds to larger flares and dips lasting for hours.

✓ The variability has generally no pattern, although the longer-lasting fluctuation have larger amplitudes.

Flickering reminds us that accretion processes are intrinsically turbulent
The hot component

FLICKERING can help in better understanding the nature of the WD accretors in SSs. It is probably related to one or more (or maybe all) these processes...

- Inhomogeneity in the accretion stream
- WD rotation
- Presence of strong magnetic fields
- Interaction of the boundary layer with the WD photosphere

Flickering reminds us that accretion processes are intrinsically turbulent
The hot component

FLICKERING can help in better understanding the nature of the WD accretors in SSs

A representative example

Z And – the only known SS with a magnetic WD

Z And B-band light curve and corresponding power spectra.

The flickering amplitude is ~0.002 mag in B and ~0.02 mag in U.

The feature at 0.6 mHz corresponds to an oscillation period of 28 min.

from Sokoloski & Bildsten (1999)

A spin period of 28 min would imply a WD magnetic field strength of B=6x10^6 G
The hot component

Flickering can help in better understanding the nature of the WD accretors in SSs from Angeloni et al. 2012
The hot component

FLICKERING can help in better understanding the nature of the WD accretors in SSs

from Angeloni et al. 2012
The hot component

FLICKERING can help in better understanding the nature of the WD accretors in SSs

We don’t have answers yet to several fundamental questions

- Why some symbiotic stars flicker and some do not?
- What is the contribution of the flickering light source to the total light?
- To which degree the amplitudes decrease from slow to rapid flares?
- To which degree these properties are characteristic for symbiotic subtypes (e.g., S-types, D-types, hard X-ray emitter symbiotics) and photometric states (outburst, quiescence)?
- Does this propriety correlate with dynamical or geometrical system parameters?
The cool giant

Several studies since the late 70’s have tried to compare isolated and symbiotic cool giants in order to point out any difference in the physical parameters which describes these stars (mass-loss rates, pulsations, dust chemistry, etc).

It is not clear if they really highlight some intrinsic differences or just mirror biased selection effects.
The cool giant

For example, it seems that **symbiotic Mirae**

- have higher mass-loss rate than isolated Mirae;
- show tighter association with extended (dust) nebulae;
- maser emission seems rarer;
- obscuration events are more frequent;
- no obvious differences in the chemical properties of dust.
The cool giant

Magnetic activity of the cool component in symbiotic systems

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ABSTRACT
I argue that cool giant components in most symbiotic binary systems possess magnetic activity on a much higher level than isolated cool giants or those in wide binary systems. Based on the behaviour of main-sequence stars, I assume that magnetic activity and X-ray luminosity increase with rotation velocity. I then show that the cool components in symbiotic systems are likely to rotate much faster than isolated, or in wide binary systems, cool giants. The magnetic activity of the cool giant may be observed as a global axisymmetrical mass-loss geometry of the cool giant (before the hot companion influences the outflow), a stochastic mass-loss process, i.e. a variation of mass-loss rate with time and location on the surface of the giant and in relatively strong X-ray emission. The variation in the mass-loss process from the cool giant may cause variation in the properties of jets blown by the hot compact companion. I conclude that symbiotic systems should be high-priority X-ray targets.

Key words: stars: AGB and post-AGB – binaries: symbiotic – circumstellar matter – stars: magnetic fields.
The cool giant – mode of mass transfer

Stellar wind or Roche lobe overflow (RLOF)?

The Roche lobe radius $R_{RL}$ versus the cool giant’s radius, as derived from the spectral type, for systems with K and M-type giants. Lines denote $R_{RL} = R$, $R_{RL} = 2R$, and $R_{RL} = 4R$, respectively.
The cool giant – mode of mass transfer

Ellipsoidal variability

V (ASAS database; Pojmanski 2002) and J (Rutkowski et al. 2007) light curves of SY Mus phased with the orbital period of 624.5 d. The ellipsoidal variability is visible only in the near infrared light (from Mikolajewska 2011).
The cool giant – mode of mass transfer

Ellipsoidal variability
The cool giant – mode of mass transfer

Ellipsoidal variability has been detected in near infrared and red light curves of over a dozen symbiotics suggesting that the giants are at least very close to filling their Roche lobes.

It is possible that tidally distorted donors and Roche-lobe overflow are quite common in symbiotic binaries with $P_{\text{orb}} \leq 1000$ days.

The presence of tidally distorted giants in symbiotic systems would also facilitate accretion disk formation.
The extremely hot radiation field of the WD (X-rays, UV) illuminates the hemisphere of the giant facing the system center of mass.

This hemisphere warms up and emits in the optical (max. effect in the U, less in V, virtually null in I)

The reflection effect has helped to discover several orbital periods
The cool giant - reflection effects

AG Peg
$P_{\text{orb}}=817$ d

AG Dra
$P_{\text{orb}}=549$ d
The cool giant - reflection effects

YY Her
$P_{\text{orb}}=574.58 \text{ d}$
The cool giant - reflection effects

$P_{\text{orb}} = 590 \text{ d}$

$Y Y \text{ Her}$

$P_{\text{orb}} = 854 \text{ d}$

$C I \text{ Cyg}$
Symbiotics as Binary stars

Orbital parameters of symbiotic stars. Shaded regions denote locations of the SyNe (lighter) and the SyRNe (darker).
Symbiotics as Binary stars - Eclipses

PU Vul (1979)

UV 1590 Å

Optical

V magnitude

JD 2,440,000+ (day)

from Sato et al. 2012
Symbiotics as Binary stars - Eclipses

Fig. 5.— A close up view of the first eclipse. Our model light curve is indicated by the red solid line, which is a summation of the eclipsed WD photosphere, a constant nebular emission of $V = 14.0$, and the RG photosphere with a sinusoidal oscillation around $V = 13.6$ (green dash-dotted line). The mid-eclipse on JD 2,444,532 is indicated by a downward arrow. See text for more details.

Fig. 6.— A close up view of the second eclipse. Observational data are taken from Kolotilov et al. (1995) (crosses) and Yoon & Honeycutt (2000) (open circles). The red solid line indicates our composite light curve which is a summation of the four components, i.e., the pulsating RG (green dash-dotted line), WD (magenta solid line), constant “nebula 1” emission of $V = 14.0$ (black solid line), and gradually decreasing “nebula 2” emission which is eclipsed by 25% (brown solid line). The RG is pulsating around its mean magnitude of $V = 13.6$. The mid-eclipse on JD 2,449,447 is indicated by a downward arrow.

from Sato et al. 2012
Symbiotics as Binary Stars - Eclipses

Fig. 7. — Light curve of PU Vul for the period JD 2,447,000–2,451,000 (upper part) and JD 2,453,500–2,457,500 (lower part). Observational data are taken from Kolotilov et al. (1995)(crosses), Yoon & Honeycutt (2000)(small open circles), Klein et al. (1994)(squares), Kanamitsu et al. (1991)(open stars), and Iijima (1989)(middle size open circles). For the lower part, observational data are taken from AAVSO (dots) and All Sky Automated Survey (ASAS) (crosses). Downward arrows indicate the central times of the eclipses, JD 2,449,447 and 2,454,362. Short vertical lines indicate epochs of the pulsation maxima of the M giant assuming a period of 218 days.
The wind of the red giant is ionized by the harsh radiation field of the WD
¡photoionization at work!

Fig. 1.—A schematic of the model

from Taylor & Seaquist 1984
The wind of the red giant is ionized by the harsh radiation field of the WD

¡photoionization at work!

The symbiotic nebula
(very) basic picture

from Nussbaumer & Vogel 1989
The symbiotic nebula
(very) basic picture

The wind of the red giant is ionized by the harsh radiation field of the WD
¡photoionization at work!

stratification effect
from Nussbaumer & Vogel 1989
The wind of the red giant is ionized by the harsh radiation field of the WD, ¡photoionization at work!

\[ N_e = 10^5 \div 10^9 \text{ cm}^{-3} \] densities are higher than in PNe

Density diagnostics: \([\text{CIII}]\lambda\lambda 1907, 1909, [\text{NIII}]\lambda 1749, [\text{NIV}]\lambda 1485, [\text{OIV}]\lambda 1401, \ldots\]

\[ T_e = 13000 \div 17000 \text{K} \] for the emission region of CIII, CIV, NV.
The symbiotic nebula

Some discrepancies between observed and model flux ratios in both permitted and forbidden emission lines brought several authors (e.g. Wallerstein et al. 1984; Nussbaumer & Vogel 1989; Nussbaumer et al. 1995) to conclude that also the hot star possesses its own wind. This evidence represented the onset of a series of studies describing

symbiotic stars as colliding-wind systems

providing a more natural explanation of the evidence of jets, accretion disks and other high-energy phenomena (e.g. Kellogg et al. 2007; Stute & Sahai 2007, 2009) that simply do not fit into a pure photo-ionization scenario.
The symbiotic nebula

symbiotic stars as colliding-wind systems

The hot and cool components are represented by the open and filled circles, respectively. The surrounding medium (I) is constituted by mass lost by the cool component before the initiation of the hot component wind (II).
The symbiotic nebula
Jets & outflows

Hen 3-1341
from Munari et al. 2005

Figure 3. Evolution of Hα and He I 5876-Å profiles between 1989 and 2004. The profiles are plotted on a logarithmic flux scale to emphasize visibility of the jets in Hα and the wind absorption signatures in He I. (a) From van Winckel et al. (1993); (b), (c), (d), (f) Echelle spectrograph at the Asiago 1.82-m telescope; (e) ELODIE spectrograph at the OHP 1.93-m telescope.
The symbiotic nebula
Jets & outflows

CH Cyg

Chandra+HST+VLA
The symbiotic nebula
Jets & outflows

R Aqr

HM Sge

© Anglo-Australian Observatory
The symbiotic nebula
Jets & outflows

The highly-collimated jet from Sanduleak’s star in the Large Magellanic Cloud
In 1977 N. Sanduleak reported on the discovery of a suspected variable emission-line object in the direction of LMC.

It became known as Sanduleak’s star (or also as LMC Anonymous).
Its real nature has remained a mystery for more than 30 years.

The object has been catalogued among symbiotic stars\textsuperscript{1,2} but the absence of any late-type stellar signatures in the optical spectra leaves this classification controversial\textsuperscript{3}.

\textsuperscript{1} Allen, D. A. \textit{ApJL}, \textbf{20}, 131-134 (1980)
Sanduleak's star in the literature

Sanduleak
1977

Kafatos et al.
1983

Michalitsianos et al.
1989

The source is some type of eruptive variable star rather than a planetary nebula

Extreme departures from normal cosmic values of N/C and N/O are found

There is similarity in the UV with η Carinae and SN1987A
Sanduleak’s star

Long-term optical light curve (Angeloni et al. 2014)

from Muerset & Nussbaumer
Magellan-Clay Telescope + MagIC

Continuum-subtracted $H\alpha+[N\text{II}]$ image

FoV: 1.4’ x 1.4’
Pixel scale: 0.07arc/pix
Exp. time: 3x900 sec
900 sec off-band
Sanduleak’s star has unveiled a highly-collimated outflow

To our knowledge, it is

- the largest bipolar stellar jet ever discovered
- the first resolved stellar jet beyond the Milky Way
Magellan-Clay Telescope + MagIC
Continuum-subtracted Hα+[NII] image
Sanduleak’s star


### Table 2. Some characteristics of known jet sources.

<table>
<thead>
<tr>
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<th>CH Cyg</th>
<th>MWC560</th>
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<td>D</td>
<td>S</td>
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<td>D</td>
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<td>$P_{\text{orb}}$ (days)</td>
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<td>1900(?)</td>
<td>1-1000</td>
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<td>?</td>
<td>170(?)</td>
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<td>$L_{\text{bol}}$ ($L_\odot$)</td>
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<td>100-1000</td>
<td>1-100</td>
<td>10^3(?)</td>
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<td>M5.5</td>
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<td>K4-M0</td>
<td>M4 (M0?)</td>
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<td>Radio</td>
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<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>A 6825</td>
<td>no</td>
<td>no</td>
<td>no(?)</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Flickering</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>no?</td>
<td>no?</td>
</tr>
<tr>
<td>$V_{\text{jet}}$, km s^{-1}</td>
<td>≤ 1000</td>
<td>200-2000</td>
<td>500-1000</td>
<td>≥ 2000</td>
<td>~ 800</td>
<td>≥ 1000</td>
</tr>
</tbody>
</table>

HST+FOC

Magellan-Clay Telescope + MagIC

R Aqr
Adopted distance to LMC: $50.1 \text{ kpc}$

Overall jet extent: $58 \text{ arcsec} \sim (14 \text{ pc})$

Length-to-width ratio: $\sim 23$

Logarithmic contour map of the $H_\alpha + [\text{NII}]$ image
The overall luminosity of the jet in H$_\alpha$+[NII] (without taking into account the central source) is $\sim 3.5 \cdot 10^{33}$ erg s$^{-1}$.

Knot A
Size $\sim 2$ pc
H$_\alpha$+[NII] luminosity: $5.6 \cdot 10^{32}$ erg s$^{-1}$

Knot C
Size $\sim 1.5$ pc
H$_\alpha$+[NII] luminosity: $1.7 \cdot 10^{32}$ erg s$^{-1}$
The overall luminosity of the jet in H\textalpha + [NII] (without taking into account the central source) is $\sim 3.5 \cdot 10^{33} \text{ erg s}^{-1}$

Nebula

Size $\sim 3 \text{ pc}$

It displays a clumpy, turbulent nature with Rayleigh-Taylor instability possibly at work.
Slit width: 0.9 arcsec
Position angle: 71°
Spectral sampling: 1.3 Angstrom/pix
Exp. time: 1200 sec
In the knots

\[
\begin{array}{c|cc}
 & A & C \\
[NII]/H\alpha & 6 & 4 \\
[OIII]/H\alpha & <0.2 & <0.2 \\
[SII]/H\alpha & <0.2 & <0.2 \\
\end{array}
\]

The extreme chemical composition is strikingly similar to what observed in the ejecta of eruptive high-mass stars, SN1987A and \( \eta \) Carinae being the most famous examples.

The overall morphology of the jet, and the wave-like modulation in the Hα radial velocity profile, make us think of a precessing emitting source.
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The symmetry in the point/velocity distribution of corresponding pair of knots strongly suggests the idea of different ejection episodes.

Recurrent (perhaps nova-like) outbursts?
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The symmetry in the point/velocity distribution of corresponding pair of knots strongly suggests the idea of different ejection episodes.

Recurrent (perhaps nova-like) outbursts?

Assuming that the jet is flowing almost in the plane of the sky, an order-of-magnitude estimate of its kinematical age is $\sim 10^4$ years.
The symmetry in the point/velocity distribution of corresponding pair of knots strongly suggests the idea of different ejection episodes.

Recurrent (perhaps nova-like) outbursts?

Assuming that the jet is flowing almost in the plane of the sky, an order-of-magnitude estimate of its kinematical age is \( \sim 10^4 \) years.

The extreme chemistry of the knots establishes a provocative link with \( \eta \) Carinae and other eruptive stars.

Is Sanduleak’s star a potential SN candidate?
“Extraordinary claims require extraordinary evidence”

Carl Sagan