Raman O VI Profile Analysis of Accretion and Bipolar Outflow in Sanduleak’s Star

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ACCRETION PROCESSES IN SYMBIOTIC STARS AND RELATED OBJECTS
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Active White Dwarf Systems: Candidate Progenitors of Type Ia Supernovae

- **Cataclysmic Variables (CVs):**
  - Semi-detached binary systems with a late type main sequence star that fills the Roche-lobe
  - Accretion from the Roche-lobe overflow

- **Symbiotic Stars (SSs):**
  - Wide binary systems with a mass losing giant
  - Accretion of the slow stellar wind from the giant
  - Higher accretion rate is expected but less studied than CVs

S. Mohamed & Ph. Podsiadlowski, 2012
Symbiotic Stars

• Present Sample
> 300 galactic SSs + 40 extragalactic SSs
( Miszalski & Mikolajewska 2014, Rodríguez-Flores et al. 2014,

• Long orbital period:
  S-type (w/ a normal giant) 200 ~ 1000 days
  D-type (w/ a Mira variable) 10 ~ 100 years

• High mass-loss rate:
  $10^{-4} ~ 10^{-7}$ $M_{\odot}$/yr depending on the stellar evolution stage.

• Complex photometric variability
  e.g., flickering in the accretion disk, rotation of the WD, stellar pulsations of the late-
type giant, recombination in the nebula, modulations associated with the orbital
  period, nova-like outbursts
Symbiotic Stars

Munari & Zwitter, 2001

Magrini et al. 2005
Symbiotic Stars

- Symbiotic stars are spectroscopically characterized by strong nebular emission lines with TiO absorption bands and continuum that are typical of a giant.
Spectral Classification Criteria
- Belczyński et al., 2000

✓ 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;

✓ Presence of the absorption features of a late-type giant; in practice, these include (amongst others) TiO, H2O, CO, CN and VO bands, as well as CaI, CaII, FeI and NaI absorption lines;

✓ The presence of the λ6825 Å emission feature, even if no features of the cool star (e.g. TiO bands) are found.
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✓ The presence of the λ6825 Å emission feature, even if no features of the cool star (e.g. TiO bands) are found.
6825 and 7082 Å Bands

• Very broad emission features at 6825 and 7082 Å are observed in about a half of symbiotic stars showing high-excitation lines e.g. [Ne V] and [Fe VII].

• In 1989, Schmid identified those features as arising from Raman-scattering of O VI λλ 1032 and 1038 by atomic hydrogen.

Schmid H. M., 1989
Raman-scattering by H I

- Raman-scattering is an inelastic scattering process.

- A far-UV photon blueward of Ly\(\alpha\) is incident upon a hydrogen atom in the ground state. Subsequently, the hydrogen atom de-excites into the 2s state, re-emitting an optical Raman-scattered photon.

- Based on the principle of Energy conservations

\[ h\nu_i = h\nu_o + h\nu_\alpha \]

- The re-emission of a photon has significantly longer wavelength than incident photon.

\[ \lambda_{RV} = \frac{\lambda_{Ly\alpha}\lambda_i}{\lambda_{Ly\alpha} - \lambda_i} \quad (\lambda_{Ly\alpha} = 1215.67\text{Å}) \]

Ly \(\beta\) 1025
(1s \(\rightarrow\) 3p)

H\(\alpha\) 6563
(3p \(\rightarrow\) 2s)

O VI 1032

Raman O VI 6825

23/11/2016 Gemini Observatory
6825 and 7082 Å Bands?
6825 and 7082 Å Bands?

Raman-scattering by H I

O VI $\lambda$ 1032 Å $\rightarrow$ **Raman O VI at 6825 Å**

O VI $\lambda$ 1038 Å $\rightarrow$ **Raman O VI at 7082 Å**
Raman O VI Features in Symbiotic Stars

- The Raman-scattering cross section for O VI:
  \[ \sigma \approx 10^{-22} \text{ cm}^2 \]

- It requires a thick neutral component with \( N_{\text{HI}} \approx 10^{22} \text{ cm}^{-2} \) that is illuminated by a very strong far-UV emission source.
Raman O VI Features in Symbiotic Stars

• The Raman-scattering cross section for O VI:

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• It requires a thick neutral component with \( N_{\text{HI}} \sim 10^{22} \text{ cm}^{-2} \) that is illuminated by a very strong far-UV emission source.

This condition is ideally met in symbiotic stars.
What is so special about Raman profiles?

- The Raman profiles reflect the relative kinematics between the neutral region and the far-UV emission region and are almost independent of the observer’s line of sight.
Accretion Flow model

- The double-peak profiles can be interpreted as a result of the kinematics of O VI 1032 and 1038 emission region associated with the accretion flow around the WD.

Lee & Kang, 2007
Asymmetric Accretion

H I Region

RED GIANT

Divergence Region (Optically thin)

Convergence Region (Optically thick)

1032

1038

1032

1038

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Asymmetric Accretion

H I Region

RED GIANT

Far-UV O VI Doublets

1032
1038
Asymmetric Accretion

H I Region

RED GIANT

Raman O VI Features

6825  7082
What is so special about Raman profiles

- The Raman profiles reflect the relative kinematics between the neutral region and the far-UV emission region and are almost independent of the observer’s line of sight.
- Nature has installed a wonderful mirror in front of the giant to provide a perfect edge-on view of the accretion flow.
Emissivity Map

- A profile comparison of two Raman O VI features could provide with the density structure in the O VI emission region.

Heo & Lee (2015)
Bipolar Outflow Model (Heo et al., in prep.)

V455 Sco (MIKE, 2015)
Bipolar Outflow Model

- The Raman-scattered features are usually strongly polarized.

- In many cases the red wing is polarized in the direction perpendicular to the polarization direction of the main part.

Spectropolarimetric observations (Harries & Howarth, 1996)
Part II.
Raman O VI Profile Analysis
A Profile Analysis of Raman-scattered O vi Bands at 6825 Å and 7082 Å in Sanduleak’s Star

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ABSTRACT

We present a detailed modeling of the two broad bands observed at 6825 Å and 7082 Å in Sanduleak’s star, a controversial object in the Large Magellanic Cloud. These bands are known to originate from Raman-scattering of O VI λλ 1032 and 1038 photons with atomic hydrogen and are only observed in bona fide symbiotic stars. Our high-resolution spectrum obtained with the Magellan Inamori Kyocera Echelle (MIKE) spectrograph at the Magellan-Clay Telescope reveals, quite surprisingly, that the profiles of the two bands look very different: while the Raman 6825 Å band shows a single broad profile with a redward extended bump, the Raman 7082 Å band exhibits a distinct triple-peak profile. Our model suggests that the O VI emission nebula can be decomposed into a red, blue and central emission regions from an accretion disk, a bipolar outflow and a further compact, optically thick region. We also perform Monte Carlo simulations with the aim of fitting the observed flux ratio $F(6825)/F(7082) \sim 4.5$, which indicate that the neutral region in Sanduleak’s star is characterized by the column density $N_{HI} \sim 1 \times 10^{23} \text{ cm}^{-2}$.

Subject headings: scattering – profile – radiative transfer – binary — Sanduleak’s Star
Sanduleak (1977)

- Strong variation of Hα emission
- Strong emission in Balmer series and [O III] 5007 and 4959
- Variable emission at He II 4686 and [O III] 4363
Sanduleak’s Star

**Kafatos et al.**
“CNO processed material”
Large overabundance of N
1983

**Michalitsianos et al.**
Similarity with η Car and SN1987A in Far-UV spectra
1989

**Allen**
“Symbiotic star candidates”
Numerous high-excitation emission lines
Presence of λ6830 bands
1980 ✓

**Belczynski et al.**
“A catalogue of symbiotic stars”
2000 ✓

**Munari & Zwitter**
“Atlas of symbiotic stars”
2002 ✓
Sanduleak’s Star

Angeloni et al.

“A giant, highly-collimated bipolar jet”
MIKE Observation

- The Magellan Enamor Kyocera Echelle (MIKE)
- 6.5m Clay Telescope, Las Campanas Obs., Chile
- Observing Date: 21, Nov. 2010
- Spectral Coverage: (Red) 4,900~9,500 Å
- Resolving Power ~ 22,000
- Exposure Time: 3 * 900 sec
Raman O VI in Sanduleak’s star

- The two Raman profiles are quite different: while the 6825 feature shows a single broad profile, the 7082 one exhibits a distinct triple-peak profile.
In order to characterize the emission regions, we decomposed the far-UV OVI emission lines into five Gaussian components based on the observed Raman-scattered features.
a) BEP and REP in the Accretion Disk

- Peak separation of the first peak and the third peak is ~ 70km/s.
  - It is consistent with a Keplerian motion with a velocity of ~ 35km/s
a) BEP and REP in the Accretion Disk

① Blue Emission Part (BEP)
- Approaching to the giant $v \approx -35 \text{ km/s}$
- Optically thin
- $F(1032):F(1038) = 2:1$

② Red Emission Part (REP)
- Receding from the giant $v \approx +35 \text{ km/s}$
- Optically thick
- $F(1032):F(1038) = 1:1$
b) CEP in the Accretion Disk

b) Central Emission Part (CEP)
- $v \sim +5\text{km/s}$
- Widely spread $\Delta v \sim 25\text{km/s}$
- Optically thin, $F(1032):F(1038)=2:1$
c) Bipolar Outflowing Region

- Discovery of the Jet
- **Red bump in the Raman O VI 6825 feature has a speed of \( \sim + 60\text{km/s} \).**
- The corresponding feature in the Raman O VI 7082 feature appears to be buried in the smooth red wing part.
c) Bipolar Outflowing Region

- One gaussian component is formed from the bipolar outflowing region.
- Moves away with $v \sim 57\text{ km/s}$
- Optically thin $F(1032):F(1038)=2:1$
d) Optically Thick Component

- $v \sim +6\text{km/s}$
- Narrow gaussian $\Delta v \sim 7\text{km/s}$
- Optically thick, $F(1032):F(1038)=1:1$
d) Optically Thick Component

Walder et al. (2008)
Monte-Carlo Simulations

- A neutral scattering region is a circle slab characterized by single column density $N_{\text{HI}}$.
- In order to describe the kinematic of emission regions, it is assumed that the scattering region is static with respect to the emission region.

**Monte-Carlo Simulations**

- $\text{O VI } \lambda 1032$
- $\text{O VI } \lambda 1038$
Monte-Carlo Simulations

- A good fit is obtained for $N_{\text{HI}} \sim 1 \times 10^{23} \text{cm}^{-2}$.

![Graph of Monte-Carlo Simulations](image-url)
Future Works

- **High-Resolution Spectroscopic Observations for Raman O VI Profile Analysis**
  - GRACES/Gemini-N. (2017A)
  - MIKE/Magellan-Clay telescope (2016B, 2017A)
  - BOES/1.5m Bohyunsan telescope

- **Spectropolarimetric Observations**
  - EsPaDonS/CFHT (2015B)?
  - BOES(spectropolarimeter)/1.5m Bohyunsan telescope
Future Works

- Narrow-band photometry centered on the Raman OVI band at 6825 Å
“I’m looking for an expert who can install OPERA pipeline to reduce GRACES data…”

Raman He II Features in Young Planetary Nebula IC 5117 (2016B GRACES/Gemini-N.)