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

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I. INTRODUCTION
**Symbiotic Stars**

- Binary system of a hot white dwarf and a mass losing giant

- A fraction of the slow stellar wind from the giant is gravitationally captured by the white dwarf to form an accretion disk.

- Present Sample
  - > 200 galactic SSs + 18 extragalactic SSs


SPH Simulation by Mastrodemos and Morris (1998)
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].
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 are the result of Raman-scattering of O VI $\lambda\lambda$ 1032 and 1038 by H I.
**O VI \( \lambda \lambda 1032, 1038 \) Å Emission Lines**

- **Resonance Doublets**
  - Isoelectronic configuration with Li (Valence electron in 2S)
  - Fine structure of 2P level: \( P_{3/2}, P_{1/2} \)
  - O VI \( \lambda 1032 \) Å: Transition \( P_{3/2} \rightarrow S_{1/2} \)
  - O VI \( \lambda 1038 \) Å: Transition \( P_{1/2} \rightarrow S_{1/2} \)

- **Flux Ratio \( F(1032)/F(1038) \)**
  - Theoretical value = 2:1
  - \( P_{3/2} \rightarrow S_{1/2} \) is characterized by a twice larger statistical weight than those for \( P_{1/2} \rightarrow S_{1/2} \).

- In the optically thick region, complicated radiative transfer effect makes \( F(1032)/F(1038) \sim 1:1 \). (Kang & Lee, 2008)
Raman O VI Features

- 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**

- The scattering cross section can be computed from the 2nd order perturbation theory in quantum mechanics.

  $\sigma \sim 10^{-22}$ cm$^2$
Raman O VI Features in Symbiotic Stars

- 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.
Raman O VI Features in Symbiotic Stars

- 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.
II. Sanduleak’s Star
Sanduleak’s Star

- Sanduleak’s star is a suspected symbiotic binary in the Large Magellanic Cloud.

- Despite the absence of any late-type stellar signatures, it is tentatively classified as a symbiotic star based on the presence of the Raman-scattered O VI features.

- The discovery of a giant, highly-collimated bipolar jet extending over almost 15 pc has shed new light on the nature of this object (Angeloni et al., 2011)
Observation

- The Magellan Inamori Kyocera Echelle (MIKE)
- 6.5m Clay Telescope, Las Campanas Obs., Chile
- Observing Date: 21, Nov. 2010
- Spectral Coverage: (Red) 4,900 ~ 9,500 A
- Resolving Power ~ 22,000
- Exposure Time: 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.

• We transformed the observed spectrum into the Doppler factor ($\Delta V$) space, which is measured by the atomic centers.
III. O VI Emission Region Model
Decomposition of O VI Emissions

Raman 6825
O VI λ1032

Raman 7082
O VI λ1038
Input Profiles Using Multiple Gaussians

1&2 Accretion disk – 2 Gaussians
3 Bipolar outflow – 1 Gaussian
4 Hot Spot – 1 Gaussian
5 Corona – 1 Gaussian

21-24 June 2016, Córdoba, Argentina
①&② Accretion Disk

- 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 disk around the WD (Lee & Kang, 2007)

Raman 6825Å features of V1016 Cyg & HM Sge
Accretion Disk

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

② Red Emission Part
- Receding from the giant \( \nu \sim +35\text{km/s} \)
- Optically thick
- \( F(1032) : F(1038) = 1:1 \)
3 Bipolar Outflowing Region

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

- A central peak in the Raman 7082 feature
  - A narrow width & optically thick component (Hot spot component)
  - (Small excess in FUSE data)

- Smooth profile in the Raman 6825 feature
  - A broad width & optically thin component
4&5 Hot Spot & Coronal Components

4 Localized Dense Part (Hot Spot..?)
- \( v \sim +6\text{km/s} \)
- Narrow gaussian \( \Delta v \sim 7\text{km/s} \)
- Optically thick, \( F(1032):F(1038)=1:1 \)

5 Extended Tenuous Part (Corona..?)
- \( v \sim +5\text{km/s} \)
- Widely spread \( \Delta v \sim 25\text{km/s} \)
- Optically thin, \( F(1032):F(1038)=2:1 \)
IV. RESULTS
Monte-Carlo Simulations

- With the decomposition of the OVI emission region and an additional assumption that the neutral region is a single component, we performed Monte-Carlo simulations.
Summary

• We present a detailed modeling of Raman-scattered O VI features at 6825 and 7082Å in the spectrum of Sanduleak's star.

• In our analysis we propose that the O VI emission region can be decomposed into five components: approaching and receding parts of an accretion disk, a bipolar outflow, a hot spot and coronal components.

• Future spectropolarimetric study of Sanduleak's star is hoped to provide strong support of our decomposition scheme.
ACCRETION PROCESSES
IN SYMBIOTIC STARS AND RELATED OBJECTS
FIRST CHILE-KOREA-GEMINI WORKSHOP ON STELLAR ASTROPHYSICS
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INVITED SPEAKERS

- Romano Corradi (Gran Telescopio Canarias, Spain)
- Denise Gonçalves (Valongo Observatory, Brasil)
- Hyosun Kim (ASIAA, Taiwan)
- Steve Margheim (Gemini Observatory, Chile)
- Mark Phillips (Las Campanas Observatory, Chile)
- Miguel Roth (Giant Magellan Telescope, Chile)
- Augustin Skopal (Slovak Academy of Sciences, Slovakia)

http://kochil-2016.com
Registration Deadline Sep 30, 2016
¡Gracias! 😊
Raman-scattering by H I

- Raman-scattering is an **inelastic scattering** process.
- A **far-UV photon** blueward of Lyα 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 conservation

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

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

\[ \lambda_{RV} = \frac{\lambda_{Ly\alpha}\lambda_i}{\lambda_{Ly\alpha}-\lambda_i} \quad (\lambda_{Ly\alpha} = 1215.67\text{Å}) \]
Profile Broadening of Raman-scattering

\[ h\nu_i = h\nu_o + h\nu_\alpha \rightarrow \nu_i = \nu_o + \nu_\alpha \]
\[ \Delta \nu_i = \Delta \nu_o \]
\[ \frac{\Delta \nu_i}{\nu_i} = \frac{\Delta \nu_o}{\nu_o} = \frac{\nu_o}{\nu_i} \]

- This relation implies that the Raman-scattered features will be \textbf{broadened by the factor} \((\lambda_o/\lambda_i)\)

- In the case of Raman-scattered O VI \(\lambda1032\) at 6825 Å, this factor is almost 6.6, resulting in a very broad emission features.
What is so special about Raman profiles

- The Raman-scattered features are usually **strongly polarized**. Related to this is the fact that they are composed of purely scattered photons without dilution from the direct flux.

- Since polarization is dependent on the viewing geometry, **time-series measurements** can be used to determine the orbital parameters.

Spectropolarimetric observations of CD−43·14304 (Harries & Howarth, 2000)
Raman O VI Features in Symbiotic Stars

• The scattering cross section can be computed from the 2nd order perturbation theory in quantum mechanics.

\[ \sigma \sim 10^{-22} \text{ cm}^2 \text{ for O VI} \]

• 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.
O VI Doublets in Sanduleak’s Star

- Large line width ~ 200 km/s
  - A Result of velocity gradients of shocks not only solely thermal

- A Small Excess in ~ -20 km/s
  - An optically thick component approaching to us
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.
Future Works

- Using flux-calibrated data will be able to constrain the column density and the covering factor of the neutral scattering region.
- Future spectropolarimetric study of Sanduleak's star is hoped to provide strong support of our decomposition scheme.