The Infrared Evolution of Sakurai's Object

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Abstract.
Infrared spectroscopy and photometry have revealed the remarkable evolution of Sakurai's Object from 1996 to the present. A cooling, carbon-rich photospheric spectrum was observable from 1996 to 1998. Considerable changes occured in 1998 as the continuum reddened due to absorption and emission by newly formed dust located outside the photosphere. In addition, a strong and broad helium 1.083 μm P Cygni line developed, signifying the acceleration of an outer envelope of material to speeds as high as 1000 km s^{-1}. At the same time the photosphere of the central star remained quiescent. By 1999 the photosphere was virtually completely obscured by the dust and the helium emission line was the only detectable spectral feature remaining in the 1-5 μm band. In 2000 emission by dust has become even more dominant, as the envelope continues to expand and cool and the helium line weakens.

Keywords: stars: individual (Sakurai's Object (V4334 Sgr)) – stars: peculiar – stars: AGB and post-AGB – stars: evolution

1. Introduction

This review is a phenomenological and chronological presentation of the IR observations of Sakurai's Object. Its basis is the 1-5 μm spectroscopy that the Keele-led team has acquired at the United Kingdom Infrared Telescope (UKIRT) during the last four years. Those data are supplemented in this paper with some of the other key infrared observations, both spectroscopic and photometric. Over much of the last four years and over much of the infrared region, emission by dust has dominated the spectrum of Sakurai's Object. However, the emphasis here is on the description and interpretation of the gaseous infrared features, as opposed to modelling the dust emission, which is reviewed by Tyne (this volume).

2. Overview

Figure 1 presents in five panels an overview of the evolution of the 1-5 μm spectrum of Sakurai's Object from 1996 to 2000, as observed at UKIRT with its facility spectrograph, CGS4 (Mountain et al. 1990). The figure contains one spectrum from each of the five years. Each spectrum consists of adjoined segments, with the resolving powers of the spectral segments typically ~200 to ~2,000. Note that in the first two years the data do not cover the entire 1-5 μm band. Some of the spectra in Fig. 1 have been published in Eyres et al. (1998, 1999) and in Tyne et al. (2000).

The 1996 spectrum reveals a photosphere in which atomic species are dominant. In 1997 the photosphere had cooled to temperatures at which molecules formed in abundance. During 1998 the photosphere became still cooler and its spectrum increasingly reddened by newly forming dust. In addition, during 1997-1998 continuum emission from the dust was becoming dominant over the photospheric emission at thermal infrared wavelengths. In 1999 the photospheric spectrum was no longer observable; at the shorter IR wavelengths it was completely obscured by dust absorption and at longer wavelengths it was not only obscured, but also overwhelmed by the dust emission. The dominance of the dust spectrum has has increased, if anything, in 2000.

Even in the highly condensed presentation of the spectra in Fig. 1 it is possible to pick out the most prominent narrow spectral features. The strongest of these are the CN absorption bands near 1.1 μm, 1.2 μm, and 1.45 μm, which were present during 1997-1998, the C_2 and CO bands observed during the same period near 1.8 μm and 2.3 μm, respectively, and the He I 1.083 μm line, which has undergone many remarkable changes since it first appeared in 1998 and has been a key to understanding the events of the past three years.

3. Year by Year Details

3.1. 1996

From the limited infrared data available in 1996 (Fig. 1) the spectrum of Sakurai's Object appears to be that of an F-type giant with abnormally strong lines of atomic carbon. The slope of the IR spectrum and the lack of CO at 2.3 μm and longward are consistent with this classification, which generally agrees with the conclusions from the far more extensive optical spectra and analysis by Asplund et al. (1997). A portion of K-band spectrum is shown in Fig. 2. The large redshift of Sakurai's

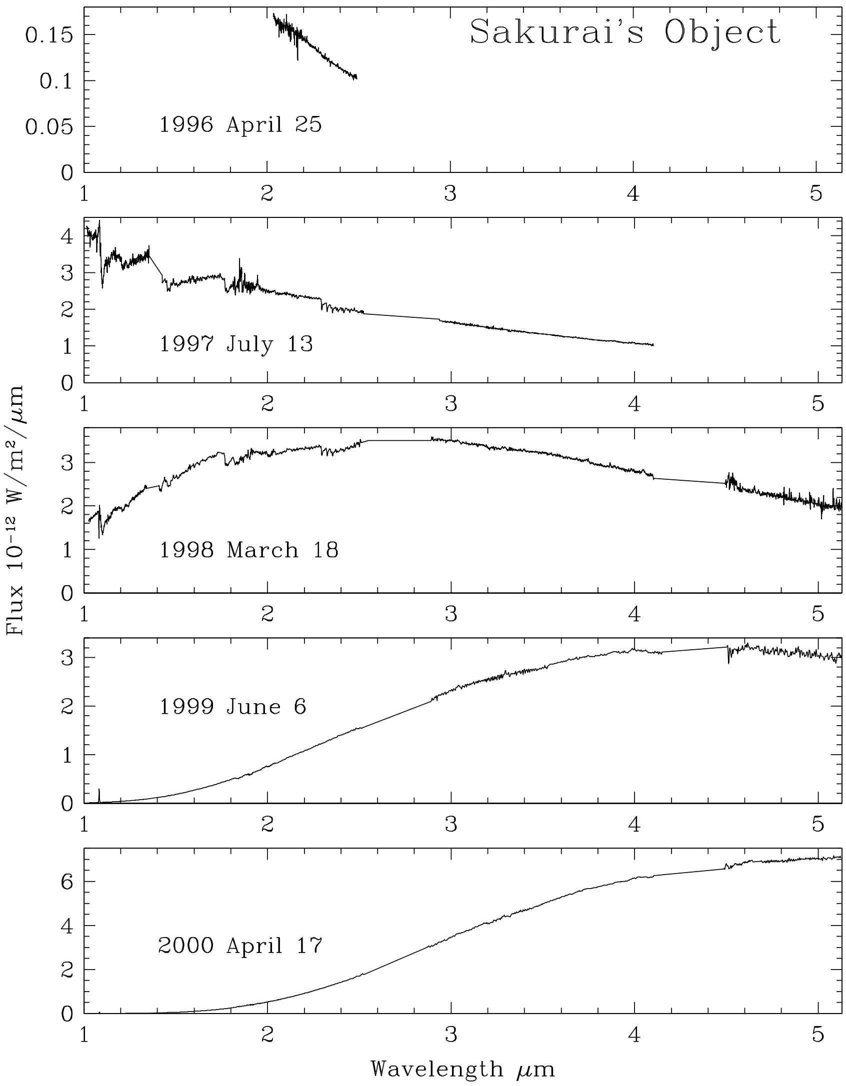

Figure 1. UKIRT/CGS4 spectra of Sakurai's Object from 1996 to 2000. The spectra are interpolated in the gaps at 1.35-1.42 μm, 2.5-2.9 μm, and 4.1-4.5 μm.

Object, 113 km s^{-1} heliocentric (Duerbeck & Benetti 1996), is readily apparent. The cluster of carbon lines near 2.12 μm is much stronger than the same cluster in the sun, as are the probable CN features near 2.143 μm. Duerbeck & Benetti (2000) observed weak Balmer lines in a spectrum obtained just one month prior to the K band spectrum; based on their result one would not expect such a strong Br γ (2.166 μm) absorption line as in Fig. 1. The line at 2.160 μm is unidentified.

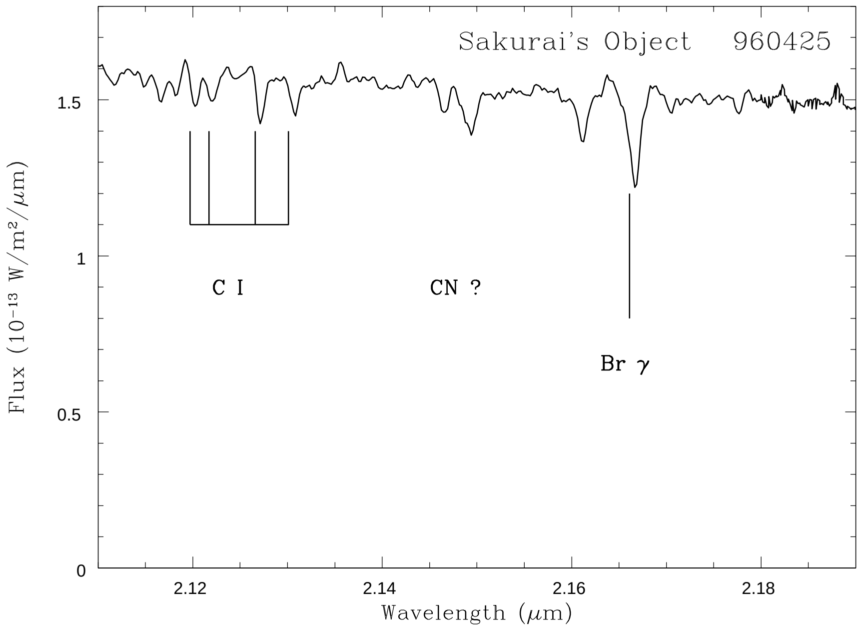

Figure 2. A portion of the K band spectrum of 1996. Vertical lines denote laboratory wavelengths of identified lines.

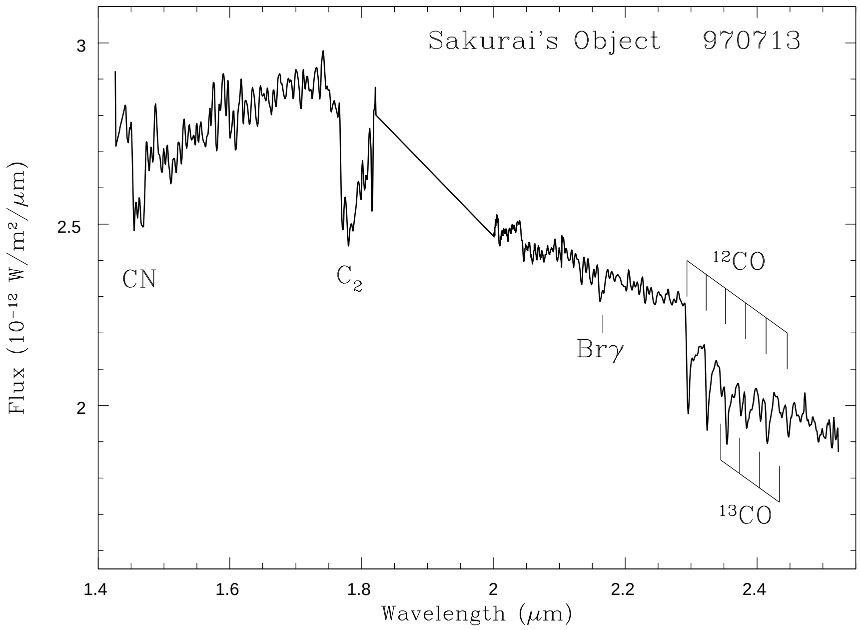

Figure 3. 1.4-2.5 μm spectrum in 1997. Vertical lines for CO are at the wavelengths of band heads.

3.2. 1997

By 1997 the photosphere of the star had cooled considerably and molecules had formed, although some atomic lines were still present. The strongest spectral features were the CN bands longward of 1.1 μm and near 1.45 μm, the C_2 band near 1.8 μm, and the CO first overtone band at 2.3 μm and longward. Most of these are shown in Fig. 3. Note that both ^{12}CO and ^{13}CO bands are present; and that at the modest resolution of this spectrum (R$\sim$800) the ^{13}CO band heads are only 2–3 times weaker than the ^{12}CO band heads. From this and a high resolution spectrum obtained the following year (Fig. 6) it is apparent that the ^{12}C/^{13}C is very low, an inference consistent with the results of Asplund et al. (1997) based on optical C_2 bands. The Br γ absorption line was still present, although weaker than in 1996. Lines of atomic strontium and carbon shortward of 1.1 μm also were present (Eyres et al. 1998). Overall the continuum continued to decrease to longer wavelengths in 1997, but more gradually than if it arose only in the photosphere, whose temperature was estimated to be 5500 K by Pavlenko, Yakovina & Duerbeck (2000). This also was apparent in the published photometry of Kamath & Ashok (1999) and of Kerber et al. (1999), and it led to suggestions that dust emission was now present. Eyres et al. fitted the excess seen in the UKIRT and ISO data to graphitic dust at 680 K. Duerbeck et al. (2000) have pointed out that free-free emission could contribute to the observed IR excess.

3.3. 1998

3.3.1. *Massive dust formation*

In 1998 more substantial changes occurred. Kerber et al (1999) combined ISO photometry with ground-based optical and near infrared photometry to demonstrate that dust was forming on a much greater scale than previously. In their Fig. 2 an obvious bump is seen in the spectral energy distribution in 1998, peaking near 4 μm. No such feature existed in 1997. The infrared spectroscopic data from 1998 are consistent with this change. The continuum no longer decreased monotonically with wavelength, but showed a peak (in F_λ just short of 3 μm (e.g., see Fig. 1). The photospheric absorption bands due to CN, C_2, and CO were still prominent, but the atomic features seen in previous years had weakened, probably due to the continued cooling of the photosphere.

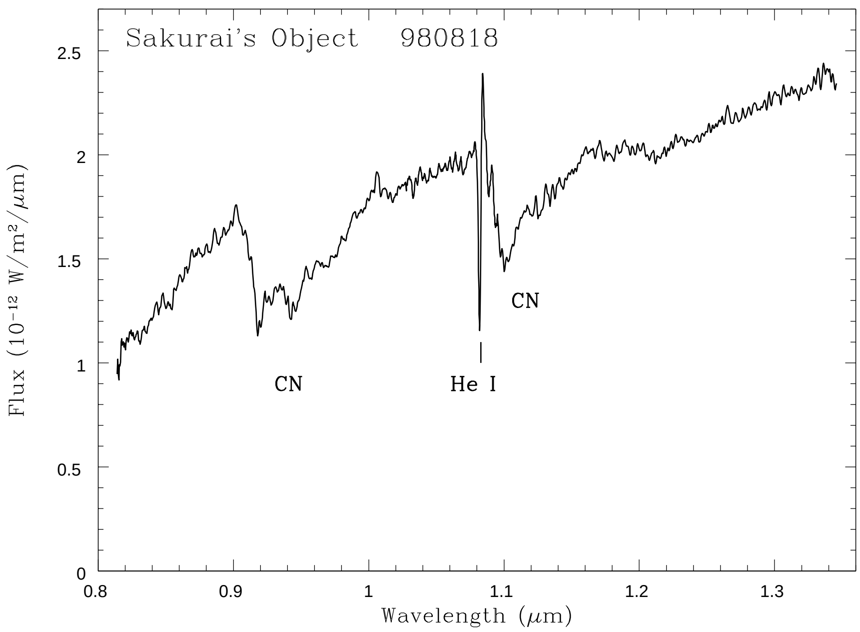

Figure 4. UKIRT/CGS4 I-J band spectrum in 1998

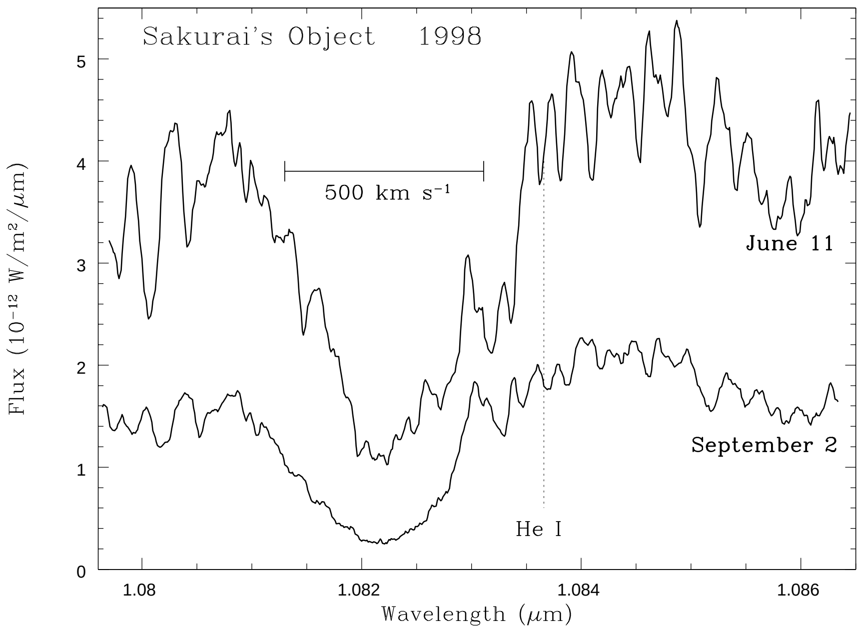

Figure 5. UKIRT/CGS4 high resolution spectra of the He I 1.083 μm line in 1998. the dashed vertical line corresponds to the wavelength of the helium line at the radial velocity of Sakurai's Object as observed on June 11

3.3.2. *The He I 1.083 μm line*

One prominent and new and spectral line appeared in 1998: the He I line at 1.083μm. It may be seen in Fig. 1, but is shown more clearly in Figs. 4 and 5. Note that the spectrum in Fig. 4 extends shortward to 0.8 μm and reveals another strong CN absorption band near 0.9 μm. The He line has a P Cygni profile, clearly signifying that mass loss is occurring. The profile is seen in great detail in the high resolution spectra (Fig. 5) from June and September of 1998. Each of the two spectra in this figure shows an absorption trough extending about 800 km s^{-1} blueward of the stellar velocity. The redshifted emission extends about 400 km s^{-1} beyond the stellar velocity. Superposed on the profile (and beyond it) are numerous narrower features, which are not identified. Some of these may be photospheric absorption lines, others might be structure in the He line profile. The slight redshift of many of these features from June to September is due to the change in the earth's orbital velocity. Clearly the gas containing the observed helium line is being accelerated outward from the star at high speed.

The 1.083 μm line is the allowed triplet 2P-2S transition of the neutral helium. The lower (2^3S) level of the transition is metastable and cannot radiate to or be radiatively excited directly from the singlet (1S) ground state. The n=2 levels can be populated from below by collisions or from higher energy states by radiative decay, for example following recombination of He II. In view of the lack of UV radiation from the central star, photoionization of helium is unlikely. He II can be produced by collisional ionization. However, in 1998 the helium line emission was weak compared to the absorption and and no recombination lines of other elements were seen. Both of these suggest that collisional ionization followed by recombination and radiative cascading was not important. We tentatively conclude that in Sakurai's Object the 2^3S level of He I was populated mainly by collisions.

It is important to note that the region in which the helium line profile was formed in 1998 was completely detached from the photosphere of Sakurai's Object. This is evident from a comparison of Fig. 5 and Fig. 6. The latter shows that a quiescent photosphere was present at same time that the high velocity outflow was occuring. No sign of high speed motions is evident in Fig. 6; the individual CO lines and the band heads are sharp. The photosphere was too hot for the dust to form there. Presumably it was the formation of dust outside the photosphere and its subsequent outward acceleration by radiation pressure that swept up and heated the gas, as manifested by the 1.083 μm line. The broad blueshifted absorption trough must have been produced by gas along the line of sight to the continuum source, which at that time was probably still mainly the photosphere of Sakurai's Object.

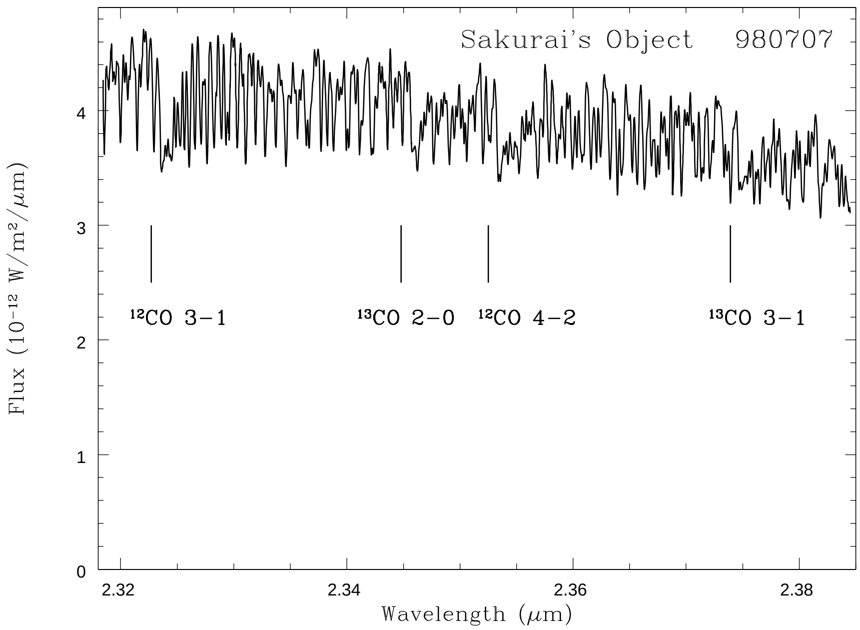

Figure 6. High resolution spectra of a portion of the CO first overtone band. The laboratory wavelengths of band heads of ^{12}CO and ^{13}CO are indicated and the heads are redshifted by roughly 0.002 μm.

The redshifted emission likely arose in regions outside of this line of sight, presumably from helium atoms in which the 2^3P (upper) level of the transition was being populated, either by absorption of 1.083 μm photons by atoms in the 2^3S level or by collisions. The great width of the absorption component suggests that in 1998 the absorption was occuring very close to where the continuum was formed and/or that a wide range of outflow speeds were present along the line of sight to the continuum source. At later times, when the ejected material becomes further detached from the continuum source and possesses a narrower range of speeds, one would expect the absorption profile to narrow and the emission to broaden. Close examination of Fig. 5 suggests that this effect was already being seen in the sumer of 1998.

Toward the end of 1998 the visual–near IR brightness of Sakurai's Object went into a steep decline. This is evidenced by the different continuum levels of the two spectra in Fig. 5, from June and early September. Spectra by Lynch et al. (this volume, see their Fig. 3) obtained at the end of September show continued and more rapid change, with the flux at 1 μm reduced by nearly an order of magnitude compared to early September. The profile of the He 1.083 μm line also was changing radically at this time. Not only was the continuum decreasing but also the broad absorption component was weakening. However, the emission feature was roughly maintaining its strength. Thus in late September the emission equivalent width had become much stronger than the absorption equivalent width (Lynch et al, their Fig. 4). The opposite was true four weeks earlier (Fig. 5).

3.4. 1999 AND 2000

In April 1999, when spectra of Sakurai's Object were next obtained at UKIRT (Tyne et al. 2000), the differences from the previous year's spectra were profound. In the 1-2.5 μm region, where previously a largely photospheric spectrum was observed, the flux was reduced, by large factors at the shorter wavelengths, and a steeply rising continuum was present (Fig. 7). Overall the peak of the spectrum had shifted to $\sim$4.5 μm in 1999, corresponding to a mean dust temperature of about 700 K, a cooling of roughly 300K in one year. By 2000 the peak had shifted longward of 5 μm (Fig. 1), indicating further cooling of the bulk of the dust. The only possibly photospheric feature still observed was a heavily obscured and veiled C_2 band near 1.78 μm (Fig. 7); this band disappeared from view later in the year. The absorption component of the He I 1.083 μm line essentially had disappeared (it is not apparent in UKIRT spectra from 1999, but a weak absorption is seen in the July 1999 spectrum of Lynch et al., this volume). The greatly decreased 1 μm continuum and continued presence of helium line emission suggests that the upper level of the He I transition was being excited mainly by collisions at that time, rather than by absorption of 1.083 μm radiation by atoms in the 2^3S state.

Figure 8 shows representative helium line profiles in 1999 and 2000. Compared to 1998 (e.g., Fig. 5) the 1999 profile was remarkably altered, with absorption all but vanished and the center of the emission close to the stellar velocity. A weak but blueshifted emission component was present $\sim$1500 km s^{-1} from the stellar velocity. The gas associated with this component was moving considerably more rapidly than any gas observed previously. No similar red shoulder was seen. However, the most highly redshifted gas should be situated directly behind the star; if so its line emission would be obscured from view.

The helium line emission that still remains in 2000 is almost entirely at positive velocities, and thus originates mostly in the rear half of the expanding envelope. Line emission at blueshifted velocities has weakened considerably since 1999, indicating that the rate of collisional excitation of the n=2 levels of He I in the front of the envelope has dropped. There appears to be no *a priori* reason this behavior of the

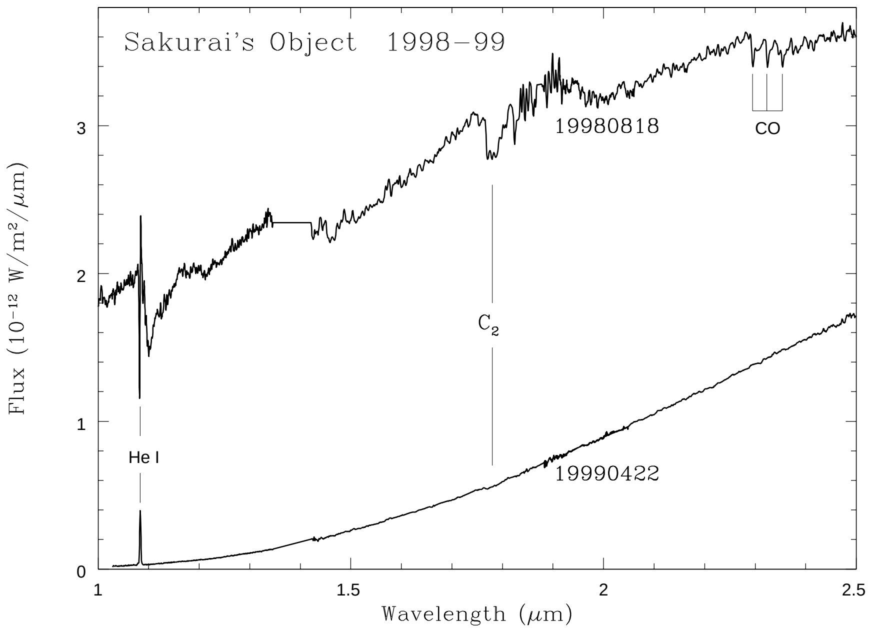

Figure 7. Comparison of 1-2.5 μm spectra in late 1998 and early 1999.

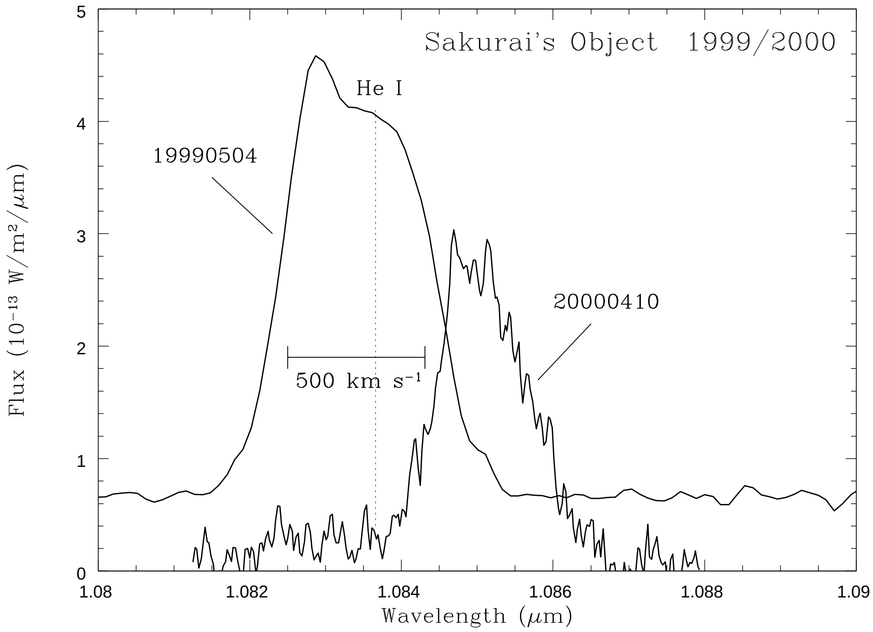

Figure 8. Helium line profiles in 1999 and 2000. The resolution of the 1999 spectrum is 60 km s^{-1}; that of the 2000 spectrum, which has been slightly smoothed, is 19 km s^{-1}. The small fluctuations in the latter are due to noise.

line profile, which naively would have been expected to remain roughly centered on the stellar velocity as it faded. The behavior suggests a non spherically symmetric geometry for the hot gas surrounding Sakurai's Object or a late and asymmetric episode of ejection or excitation.

4. Future IR Observations

The born again star at the center of Sakurai's Object is now obscured from view, even at infrared wavelengths. Moreover, the peak of dust continuum has now shifted longward of 5 μm, beyond where most previous infrared measurements were concentrated. The only gaseous spectral feature remaining in 2000, the He I 1.083 μm line, is fading rapidly and may well be undetectable by 2001. Until the veil of dust lifts and the further evolution of the the central star can be followed directly, the most important observational needs are infrared photometry across all ground-based windows and IR spectroscopy covering the 10 and 20 μm windows, in order to witness the further evolution of the dust envelope.

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