The Real-Time Evolution of Sakurai's Object and other (V)LTP Objects

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Outline

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- Overview of known (Very) Late Thermal Pulse (LTP/VLTP) events in our galaxy.
- Brief history of Sakurai's object. 2004 observations.
- The new evolutionary model needed to explain Sakurai's object.
- An update on the 2005 observations of Sakurai's object.
- The 2005 VLA observations of V605 Aql.
- The 2004 INT and 2005 VLA observations of CK Vul.
- Conclusions.
- Future Work.

Evolution in the HR diagram

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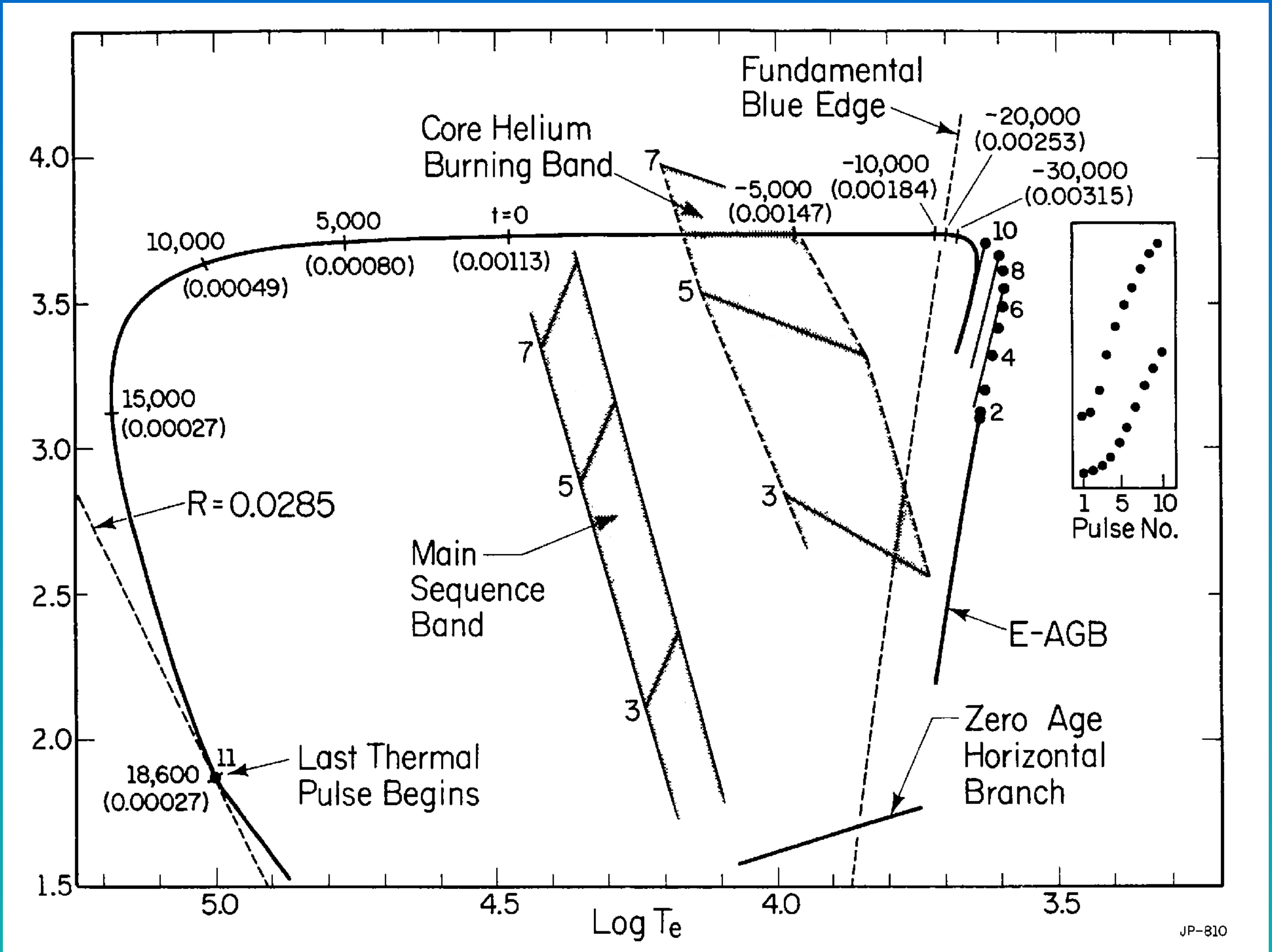

(V)LTP Events in our Galaxy

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- The brightening of V4334 Sgr was discovered in 1996 by the Japanese amateur astronomer Yukio Sakurai, and the star is now commonly named after him (Nakano et al. 1996, IAU Circ. 6322). The pulse must have occurred around 1992, but was initially too faint to be observable.
- Only one other VLTP event is known in the 20th century: V605 Aql. It was discovered in 1918, but the object quickly became obscured by dust (just like Sakurai's object), and only one contemporary spectrum exists (Clayton & de Marco 1997, AJ, 114, 2679).
- In previous centuries CK Vul (1670) and FG Sge (< 1894) may also have been LTP or VLTP events.
- The central stars of hydrogen poor [WC] planetary nebulae and the cooler hydrogen-deficient and carbon-rich R CrB stars may also be descendants of (V)LTP events.

Sakurai's Object

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- Sakurai's object (17^h 52^m $32^s.701$ -17^o 41' 07''.74 J2000) was initially assumed to be an anomalous nova. When it was discovered that the star was hydrogen deficient, it became apparent that this was a VLTP event.
- Before the VLTP event, V4334 Sgr was the core of an unknown planetary nebula. In 2004 we obtained [O III] images using FORS1 on the VLT, and 8.6 GHz radio data with the VLA. The old PN has been detected in both data sets. It is circular with a diameter of 41”, the bright inner ring has a diameter of 29”.
- This nebula is still visible because the O^{2+} ions did not have time yet to recombine. Hence they have a “memory” of conditions before the VLTP. Analysis of this spectrum showed that the old PN had already entered upon the cooling track (Kerber et al. 1999, A&A, 344, L79; Pollacco 1999, MNRAS, 304, 127). It was therefore faint and had eluded detection.

Sakurai's Object (2)

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- During the VLTP event, the central star ingested part of the surface material into deeper layers where it was burned. The remainder has been ejected, exposing the hydrogen-deficient layers below.
- The expelled material is now moving away from the star at a velocity of approximately 350 km/s (Kerber et al. 2002, ApJL, 581, L39) and will eventually form a new hydrogen-deficient planetary nebula.
- Initial spectra of the ejecta showed strong C_2 absorption bands, indicative of a carbon-rich molecular chemistry (Asplund et al. 1997, A&A, 321, L17), but no dust.
- Later dust formation did start, leading to significant circumstellar absorption. The central star is now very faint (V=23 mag), and can only be observed with 8-m class telescopes (Duerbeck et al. 2000, AJ, 119, 2360).
- The new ejecta have recently been detected in [N II] and [O II] lines, as well as radio emission. Radio observations in 1998 did not detect the central source, indicating that the reheating of the central star has now started.

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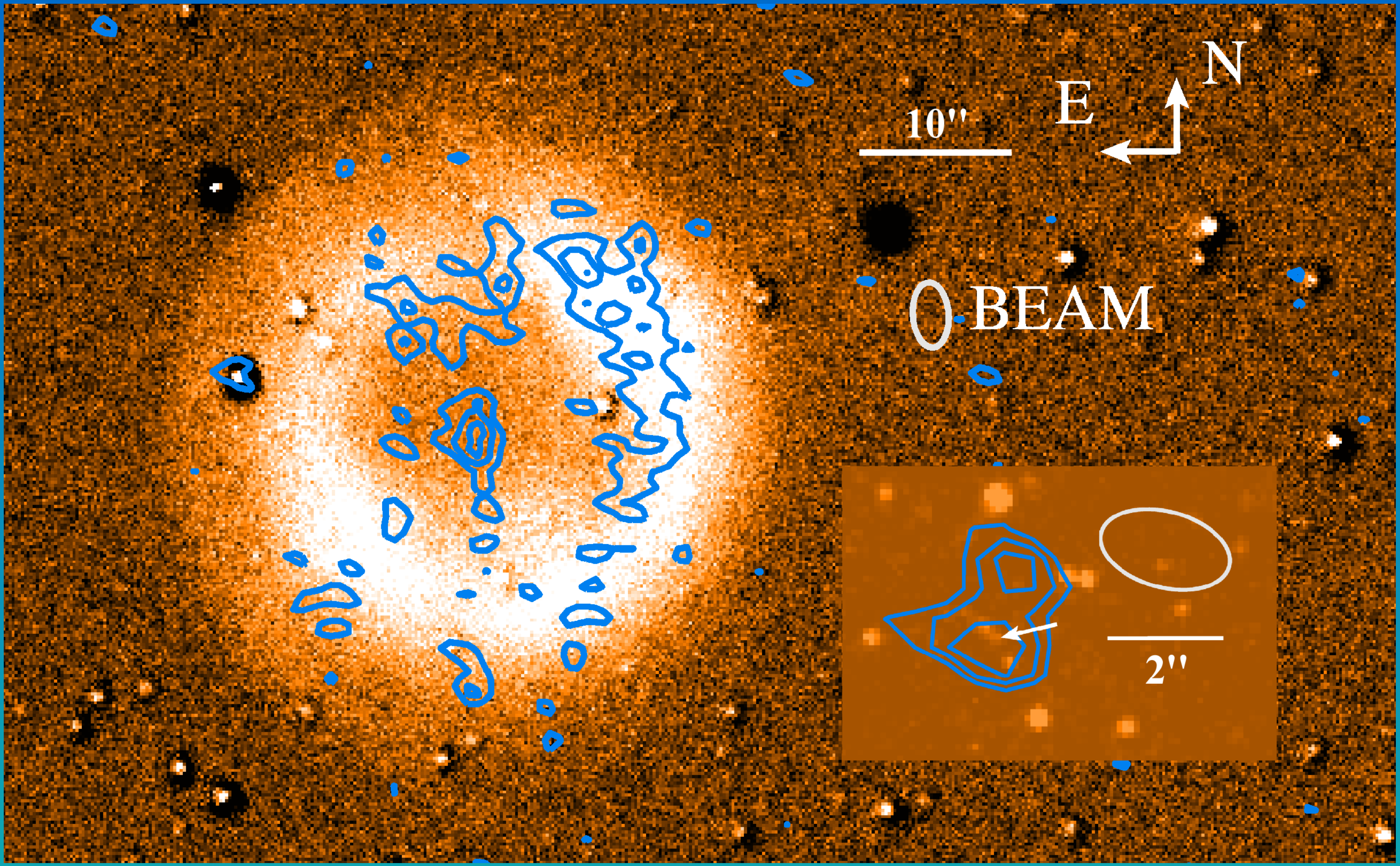
Hajduk et al., 2005, Science, 308, 231



The New Evolutionary Model

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- The central star evolution is progressing roughly 100x faster than predicted by existing theories. This is possibly the fastest rate of evolution ever observed!
- The big discrepancy between the predicted and observed evolutionary speed forced us to create a new evolutionary theory that was in agreement with the known facts at the time (Herwig, 2001, ApJ, 554, L71).
- During a VLTP event, the small remaining H-rich envelope is convectively ingested into the He shell, resulting in additional rapid H-driven nuclear flash burning. The depth at which this process occurs sets the timescale for the evolution during the VLTP event.
- Our new models parametrically include the buoyancy effect of rapid nuclear burning on convective turbulence in the He-shell flash zone. This reduces the convective mixing efficiency and accelerates the evolution, because nuclear energy from fast proton capture is released closer to the stellar surface.

The New Evolutionary Model (2)

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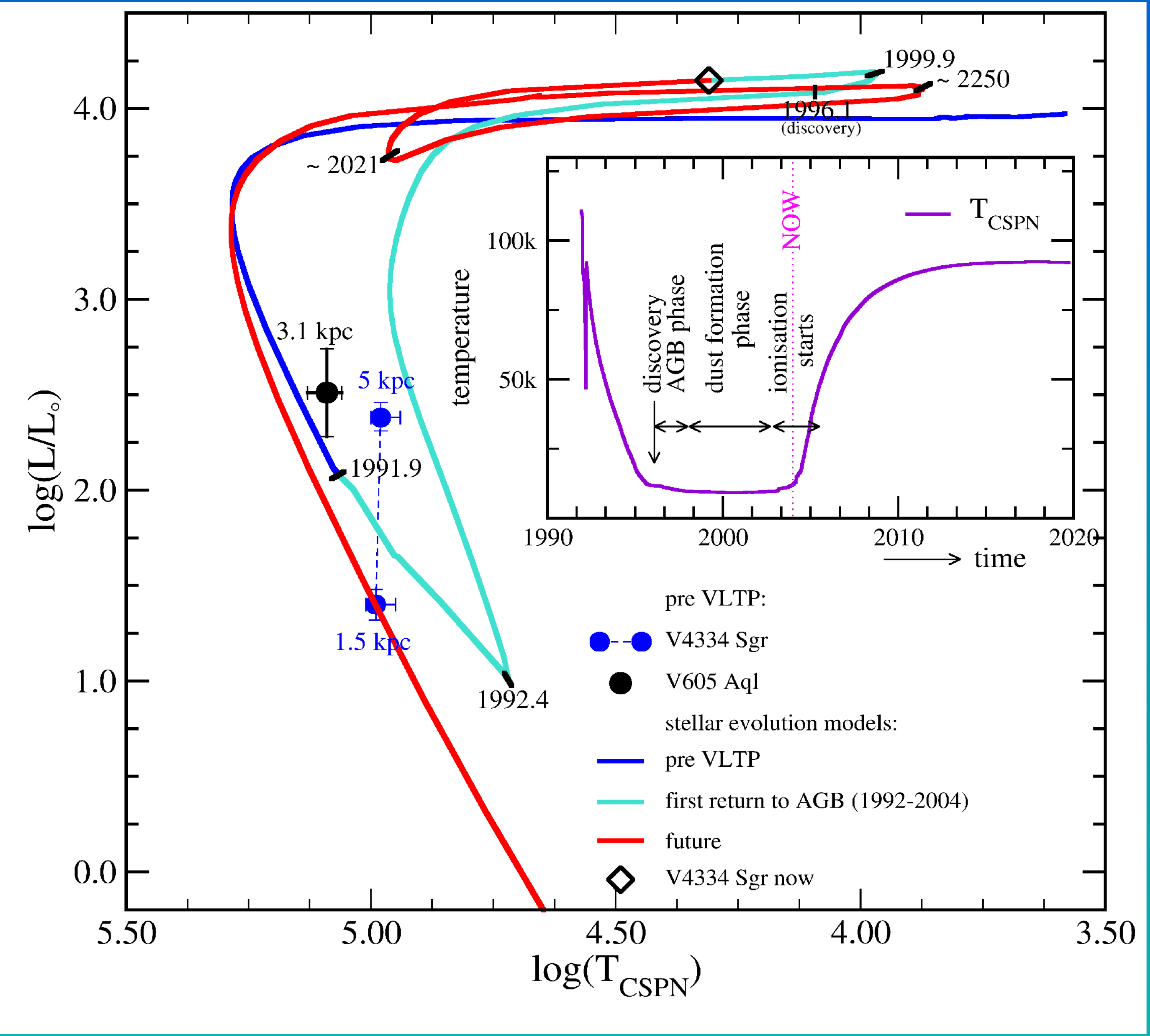
- The new model produces a double-loop structure in the Hertzsprung-Russell diagram. The first (very fast) loop is a result of the energy production of the H that is mixed into the top of the He shell. The second loop is a result of the “regular” He flash depositing its energy deeper in the He shell.
- The new model not only reproduces the fast evolution of Sakurai's object, it also explains the high $^{13}C/^{12}C$ isotope ratio, and the observed production of Li (Asplund et al., 1999, A&A, 343, 507).
- A strong prediction of our new model is that the reheating of the central star will occur equally fast. The central star will evolve from its current temperature of 20,000 K to 80,000 K within the next 10 years!

Hajduk et al., 2005, Science, 308, 231



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2005 VLA Observations

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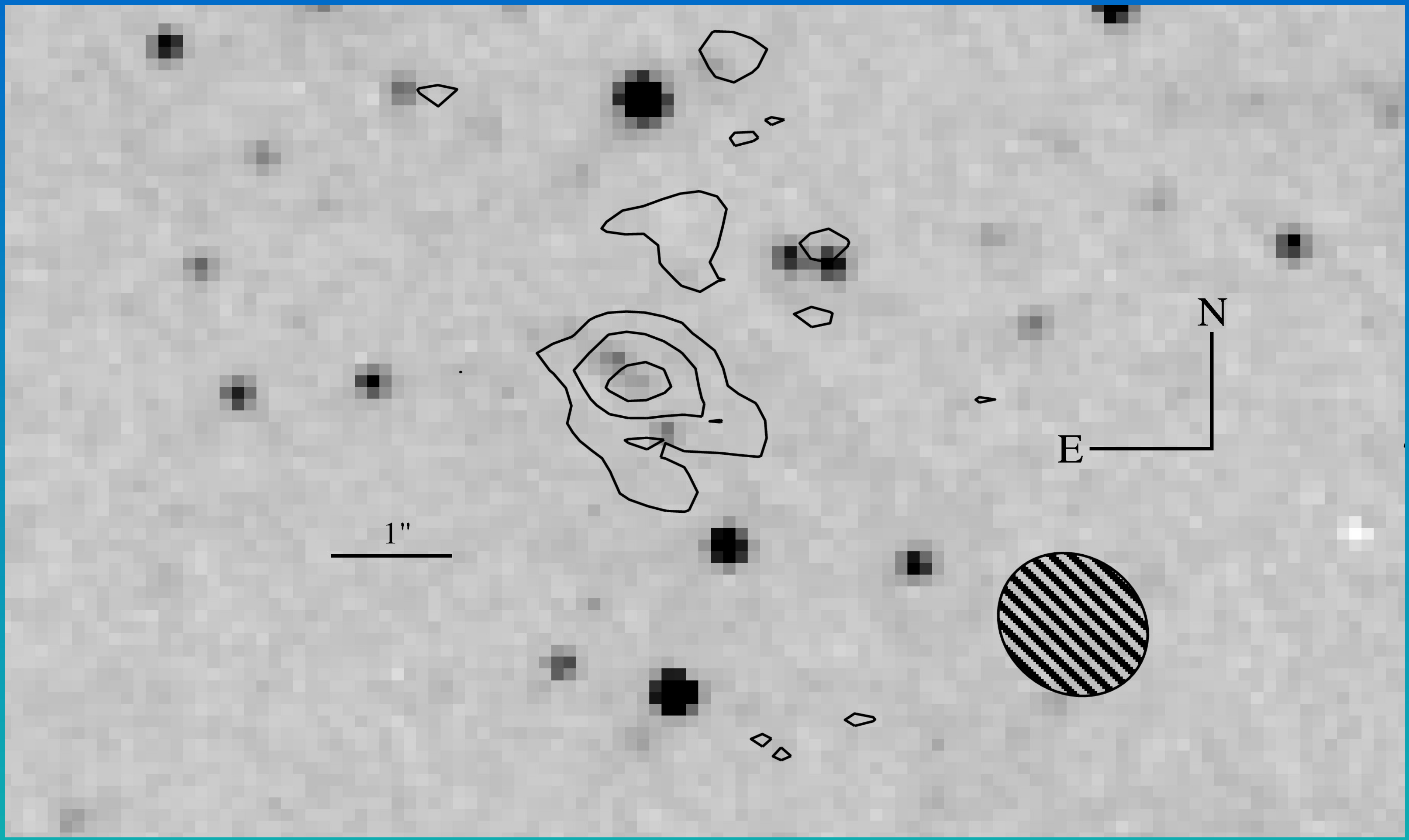
- During 2005 we obtained new VLA data at 5 and 8 GHz in the AnB configuration. This configuration achieves higher angular resolution than our earlier observations.
- We detected the source at 8 GHz. This yielded a flux of 80 ± 30 μJy, in agreement with the 2004 detection. The estimated size of the object is 1.0 x 0.5 arcsec, which is smaller than reported in Hajduk et al. (2005, Science, 308, 231). The latter value was already considered uncertain due to the noise and nebular background. The suspected bipolar morphology could not be confirmed either.
- We did not detect Sakurai's object at 5 GHz with a 3σ upper limit of 50 μJy/beam. This indicates that the radio emission is optically thick at 5 Ghz. Assuming T_e = 4500 K (Hajduk et al. 2005) and a filling factor of unity this yields $\Theta \leq 20$ mas, much smaller than observed. This could indicate a low filling factor, such as a thin shell or a very clumpy medium.

Hajduk et al., 2006, in preparation



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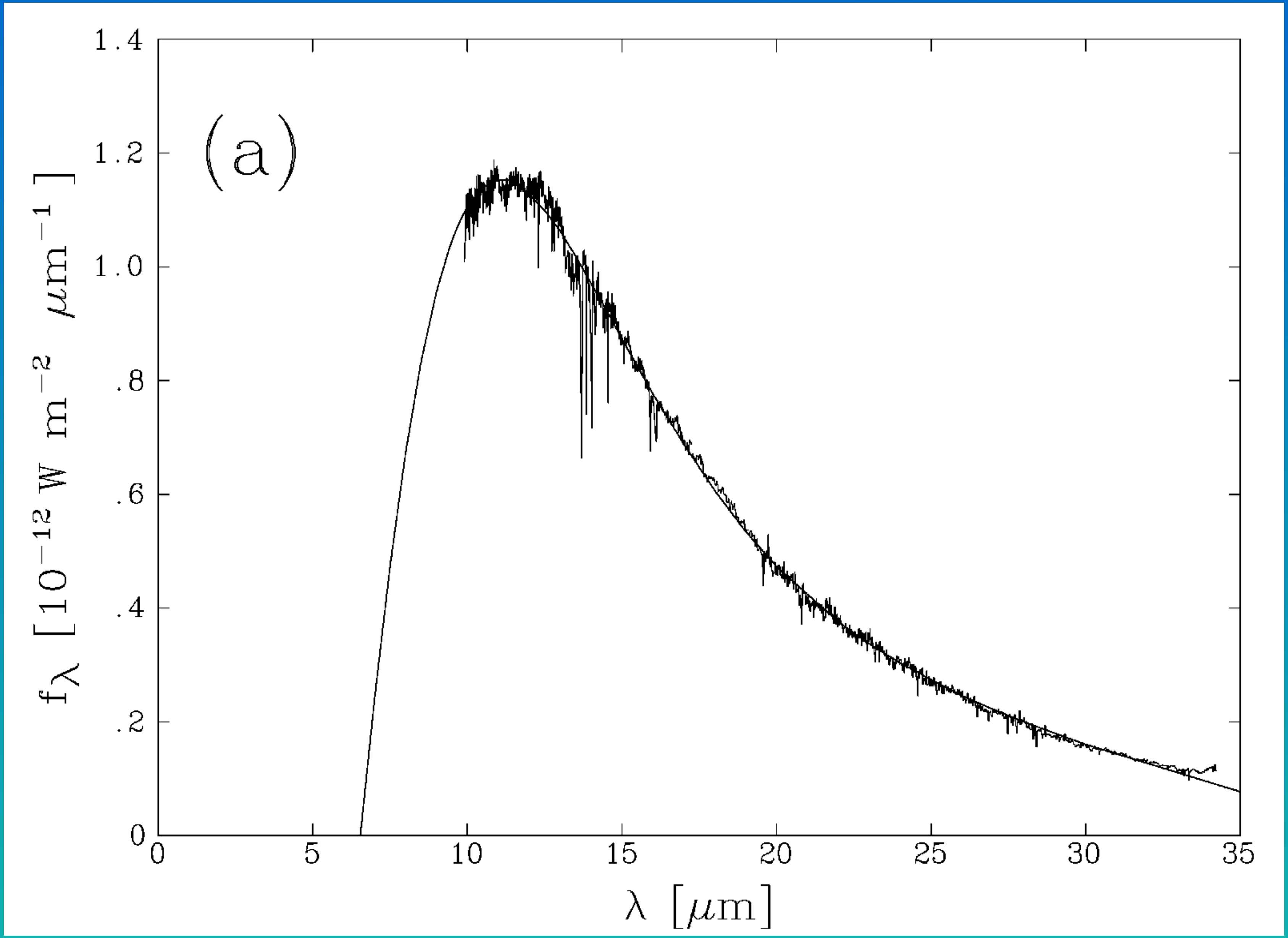
2005 optical/IR observations

- In 2005 we obtained low-resolution optical spectra with FORS1 on the VLT.
- Full analysis of the spectra is not yet complete, but first indications are that there are no big changes w.r.t. to the Kerber et al. (2002, ApJL, 581, L39) spectrum.
- A higher resolution spectrum does show changes in the individual velocity components.
- In April 2005 we also obtained an IR spectrum with IRS aboard the Spitzer Space Telescope (Evans et al., 2006, MNRAS, submitted). The spectrum shows absorption bands of HCN and polyyne molecules, but no atomic emission lines. In particular the [Ne II] 12.8 μm line has not been detected. This is one of the first lines that is expected to appear when reheating of the central star progresses.
- The high $^{13}C/^{12}C$ ratio of the absorbing molecules implies that the hydrocarbon-bearing gas must have originated in the very late thermal pulse.

Evans et al., 2006, MNRAS, submitted



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V605 Aql

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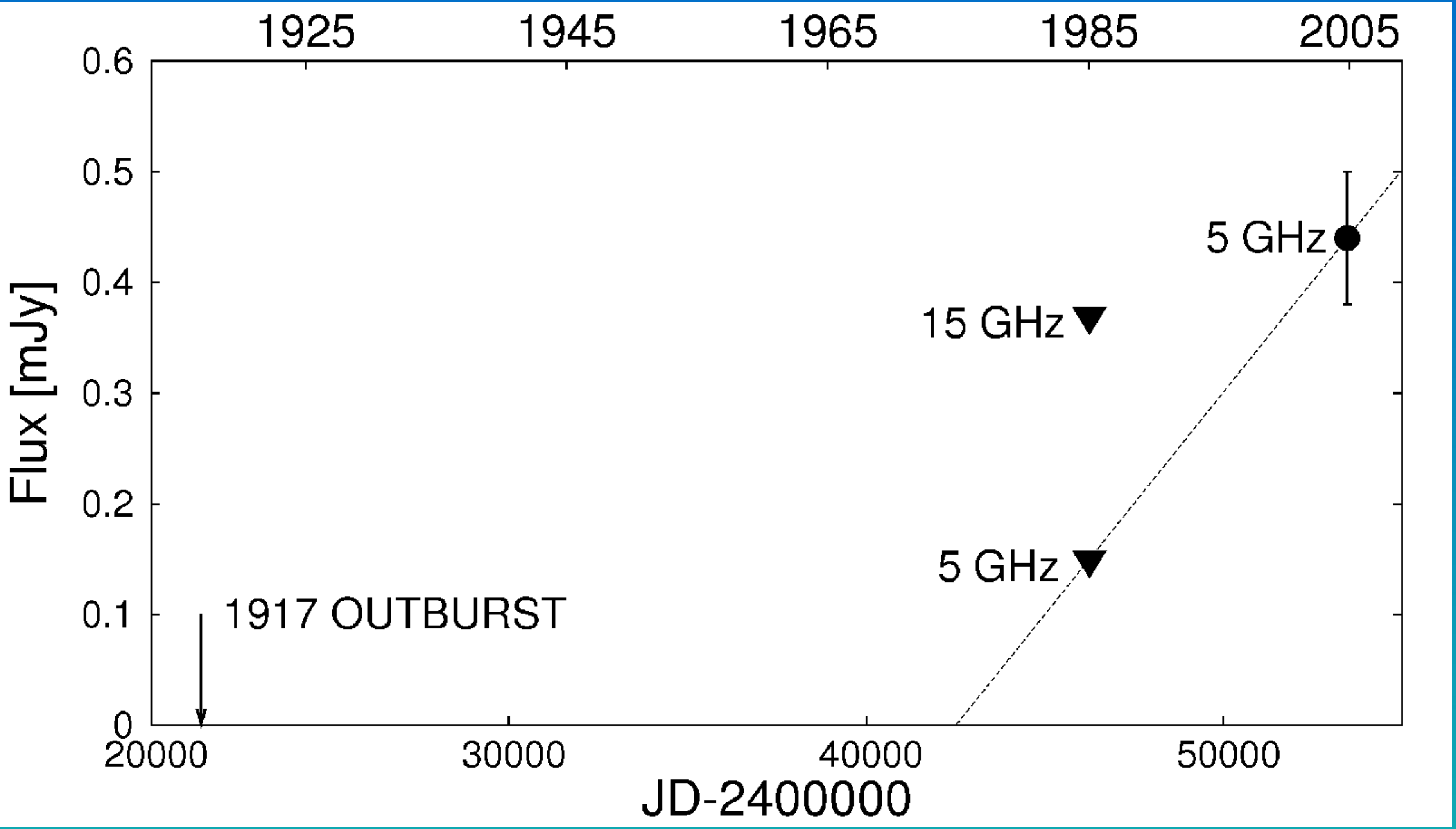
- This object is sometimes called Sakurai's “older twin”. It erupted around 1917. It is the central star of an older planetary nebula (A58). The star is still very reddened and faint (V = 23 mag). It has a WR type spectrum (Seitter 1987, ESO Messenger, 50, 114).
- We observed V605 Aql with the VLA on 4 April 2005. The flux was 440 ± 50 µJy at 5 GHz in B configuration, the angular extent 0.7” x 0.3”. The angular extent is consistent with optical observations (e.g., Bond & Pollacco 2002, Ap&SS, 275, 1)
- Previous observations by Rao et al. (1987, JA&A, 8, 227) using the VLA only achieved upper limits of 150 µJy at 5 Ghz, and 370 µJy at 15 GHz.
- This shows that the radio flux has increased considerably since 1987. This could be due to a decrease in optical depth (expansion of the ejecta) or an increase in emission measure (e.g. due to increased stellar temperature).
- The latter is suggested by changes in the spectrum of the core (Kimeswenger 2003, Rev. Mex. Ser. Conf., 15, 75).

Hajduk et al., in preparation



CK Vul

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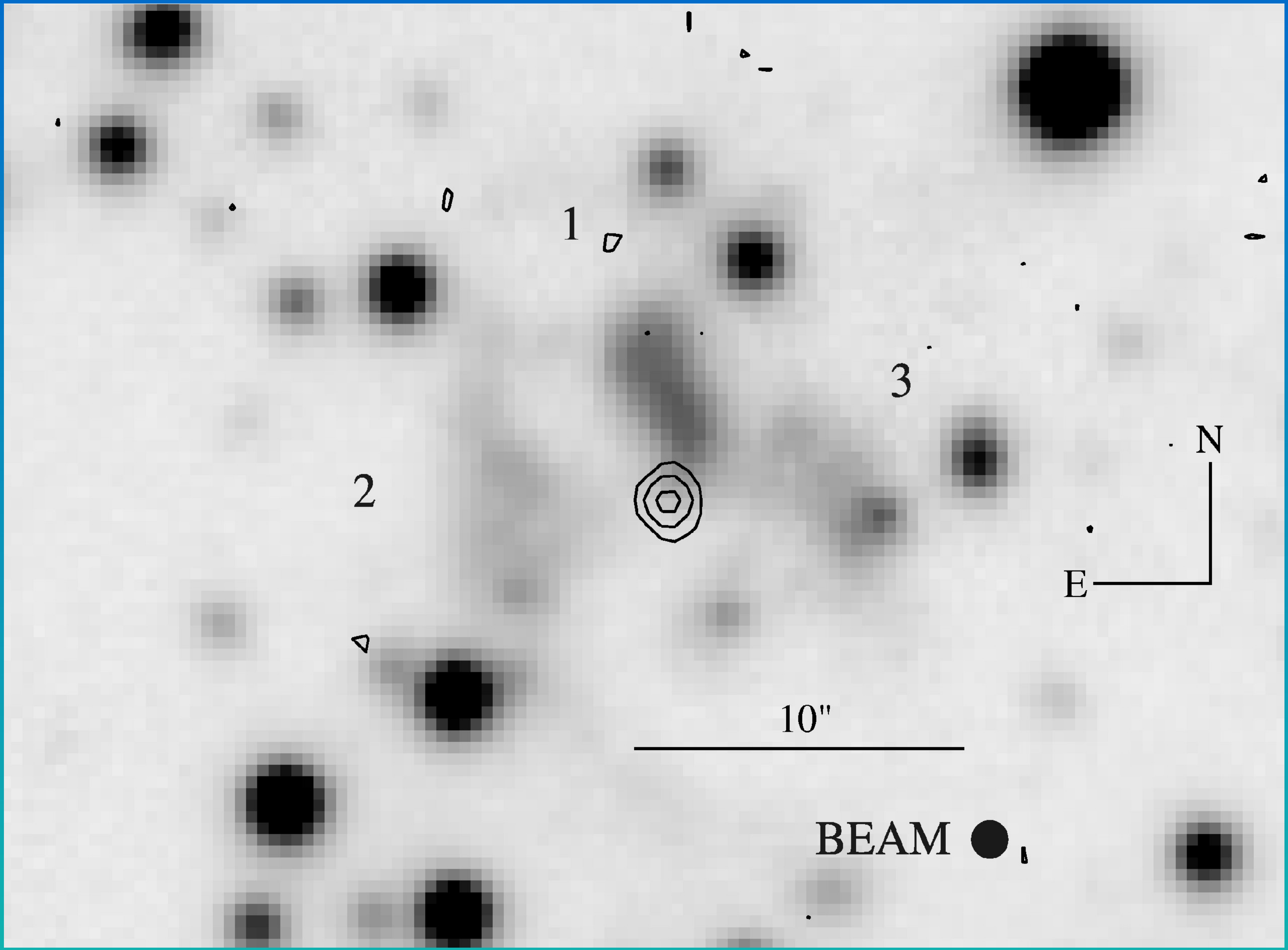
- This object was first observed in 1670. Its nebula shows highly reddened emission lines of H I, [N II], [O III], and [S II], but the central star has not yet been found. This, and other unusual properties, make it unlikely that CK Vul is an ordinary nova. The observations better fit the hypothesis that this is a VLTP object (Evans et al. 2002, MNRAS, 332, 35), although alternative theories exist (e.g. Kato 2003, A&A, 399, 695).
- We observed CK Vul with the VLA on 4 April 2005. The flux was 1.46 ± 0.05 mJy at 5 Ghz in the B configuration, the angular extent is less than 0.5”. The emission is placed at the center of the observed nebulosities.
- No Hα+[N II] counterpart for the radio emission is known. This could imply that there is significant circumstellar extinction or that the radio emission is non-thermal.
- Assuming the radio emission were optically thick and the filling factor unity would yield θ = 0.1”. Hence the upper limit for the angular extent implies that the optical depth at 5 GHz must be at least 0.04.

Hajduk et al., in preparation



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CK Vul (2)

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- Evans et al. (2002, MNRAS, 332, 35) report on observations of the IR SED of CK Vul. The observations are consistent with a two-component model: a bigger and cooler shell (25 K) with silicate grains, and carbon-rich shell with a temperature of 550 K and very small angular extent.
- The latter shell may be associated with the radio emission based on angular extent, but the evidence for this is not conclusive. The very compact nature suggests that this is a circumstellar disk.
- The slope of the SED between 450 µm and 850 µm is inconsistent with the dust emission model, suggesting that non-thermal radio emission is present at 850 µm. We are currently analyzing 8 GHz data to investigate this possibility further.
- Comparing the 2004 IPHAS Hα image with the 1991 observations of Naylor et al. (1992, MNRAS, 258, 449) reveals that knots 4 & 5 have moved away from the central position at a projected velocity of roughly 100 and 200 km/s, resp. Their displacement is consistent with an origin during the 1670 event.

Hajduk et al., in preparation

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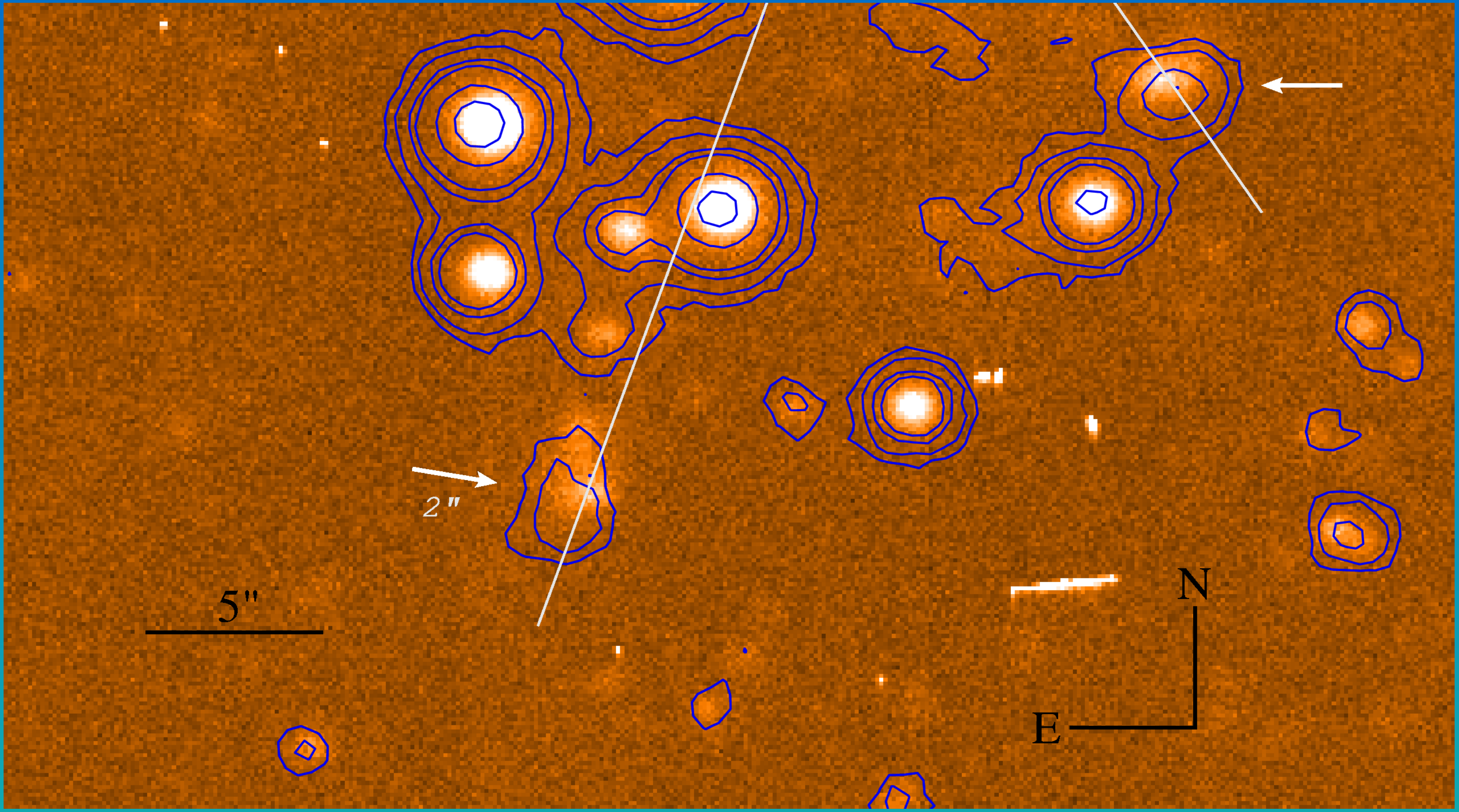
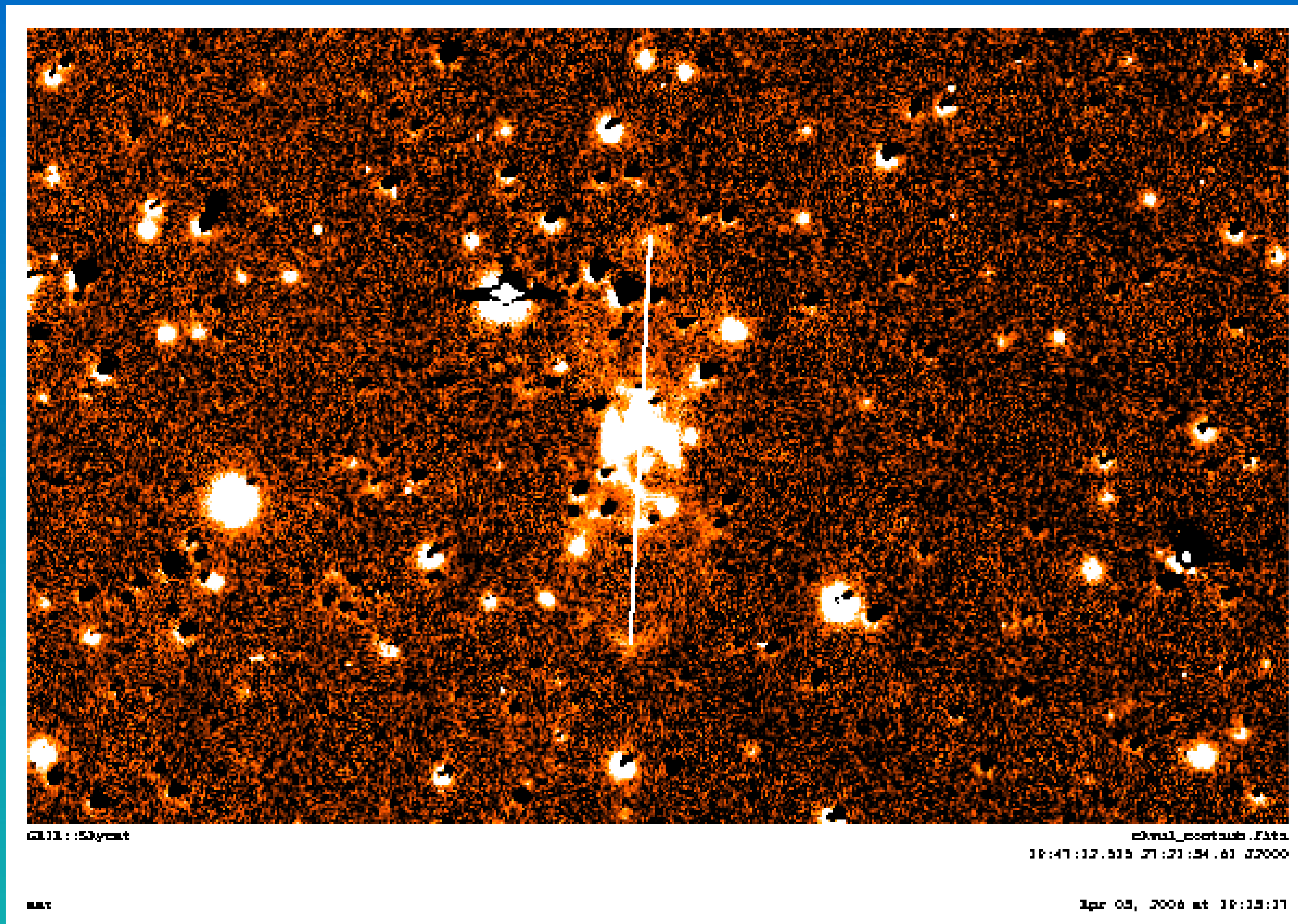


Hajduk et al., in preparation



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Conclusions

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- We have obtained optical and radio observations of Sakurai's object that show that photoionization of the new ejecta has begun. We are witnessing the birth of a new hydrogen-deficient planetary nebula!
- Earlier radio observations from 1998 did not show any signs of ionization. This indicates that the reheating of the central star has begun between 1998 and 2004. This is consistent with the predictions of our new evolutionary model for this object. There is no apparent evidence for an increase in ionization between 2004 and 2005.
- We obtained the first radio detection of V605 Aql at 5 GHz. The radio flux has increased considerably since 1987. The current rate of evolution is surprisingly steep considering the date of the VLTP event.
- We obtained the first radio detection of CK Vul. The radio source has no counterpart in our Hα+[N II] image and is unresolved. The radio emission may be non-thermal and associated with a circumstellar disk. The Hα+[N II] knots identified by Shara et al. (1982, 1985) are confirmed as the ejecta from the 1670 event due to their proper motion. We also discovered a large bipolar structure which may form the complete ejecta from the 1670 event.

Future Work

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- Our new evolutionary model predicts that the temperature of the central star will rise to 80,000 K within the next 10 years.
- This will create spectacular changes in the emission line spectrum and the radio emission from the CS envelope. These changes will be easy to detect.
- It is our goal to obtain optical and IR spectra using the VLT and UKIRT, and radio data using the VLA, on a yearly basis.
- These data will be modeled with Cloudy to determine the evolution of the central star temperature with time. This will be an important test for our new model, as well as any other model that will be constructed in the future.
- VLA observations, as well as VLT FORS1/2 observations for 2006 have been obtained and will be analyzed soon.
- We will also monitor the optical / IR / radio evolution of other (V)LTP objects.