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The 17th century eruption of CK Vul

Was it a massive AGB star?

T. Kamiński[1,2], K. M. Menten[3], R. Tylenda[4], N. A. Patel[1], and J. M. Winters[5]

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA, USA,
[2] Submillimeter Array fellow, e-mail: tkaminsk@cfa.harvard.edu,
[3] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[4] Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Rabiańska 8, 87-100 Toruń
[5] IRAM, 300 rue de la Piscine, Domaine Universitaire de Grenoble, 38406, St. Martin d'Héres, France

Abstract. CK Vul erupted in 1670–72 and has been considered the oldest nova-like object known to astrophysics. The observational characteristics of the outburst, known from ancient records, and properties of the remnant, inferred with modern instruments, rule out a classical-nova scenario for the 17th century eruption. It was proposed that Nova 1670 was a result of a stellar merger and is similar to the class of eruptive stars known as red novae or 'intermediate-luminosity optical transients' (ILOTs). Most recent sensitive observations of CK Vul obtained mainly with the IRAM-30 m and APEX telescopes reveal a cool molecular remnant of a very unusual chemical composition. The derived molecular and isotopic abundances suggest that a massive star might have been involved in the ancient eruption.

Key words. Stars: mass-loss - Stars: peculiar - circumstellar matter - Submillimeter: stars - Stars: individual: CK Vul - novae, cataclysmic variables

1. Introduction

CK Vul was observed in outburst in 1670–72 as a very bright "new star" and is the first documented nova known to modern astrophysics (Shara et al. 1985). The outburst was unusual: it lasted over two years; the light curve displayed three peaks; and the object appeared reddish in color. This characteristic does not agree with what is observed in classical novae. What was it then? In recent years, a new class of explosive objects was identified, known as 'red novae' or red transients. They are more luminous than classical novae but less luminous than supernovae and hence are also often called 'intermediate-luminosity optical transients' (ILOTs). After their outbursts, they appear red owing to low effective temperatures (∼2000 K), and produce copious amounts of molecules and dust. They erupt as a consequence of a stellar merger (Tylenda & Soker 2006). This was most spectacularly confirmed by observations of V1309 Sco which was an eclipsing binary before its explosion as a red nova in 2008. Pre-outburst photometry of V1309 shows a system with a shortening orbital period, providing a direct view on a spiraling-in process that eventually led to a merger (Tylenda et al. 2011). Mergers do happen before our eyes in real time! While Nova 1670 had all the observational signatures of a red nova (Kato 2003; Tylenda et al. 2013), we need more observational evidence that it erupted in a stellar-merger event.

2. Rich molecular remnant and nuclear ashes

In 2014 using the Atacama Pathfinder Experiment 12 meter telescope (APEX), we discovered bright and chemically complex molecular gas in emission at the location of CK Vul (Kamiński et al. 2015). The discovery was followed up with the IRAM-30m telescope. A line survey in the 90–345-GHz atmospheric windows revealed lines from a plethora of molecules. A sample spectrum is shown in Fig. 1. Among the identified 27 species are simple diatomic species and more complex polyatomic molecules including organic species such as CH_2NH, HC_3N, CH_3CN, CH_3OH, and CH_3NH_2. The inventory of molecules is most unusual and does not resemble any of the typical millimeter and submillimeter-wave stellar sources such as AGB and post-AGB stars, supergiants, and certainly not supernovae.

The molecular inventory does not indicate which chemistry type dominates in the remnant. The usual circumstellar chemical classification, carbon- or oxygen-rich, is not adequate for CK Vul. Although we find many carbon-bearing species in CK Vul, we also observe oxides, SO and SO_2, which are never present in carbon-rich envelopes; there is also an unusual variety of N-bearing species. This strongly suggest that the molecules formed from material of non-solar elemental composition and that perhaps parts of the remnant are characterized by different abundance ratios of the CNO elements. There is also circumstantial evidence for an enhanced abundance of florine, as traced by emission of AlF.

Another confusing aspect of the molecular inventory is the presence of complex species whose formation usually takes millenia and involves catalysis and processing on icy dust mantles in most known astrophysical environments. Yet, in CK Vul they must have formed within the last 350 yr or less. This indicates that the circumstellar chemistry that produced the molecules was also very unusual. Ion chemistry is a viable option to explain some polyatomic species in CK Vul but this scenario would require a presence of a central photoionizing source, which has never been observed directly in CK Vul, or a presence of strong shocks producing ultraviolet radiation.

For almost every molecule identified in CK Vul, its rare isotopologues are also detected. This is illustrated with sample profiles of the CO and HCN isotopologues in Fig. 2. We observe lines of molecules containing ^{17,18}O, ^{13}C, ^{15}N, and ^{28,29}Si. Species containing ^{15}N and ^{17}O are not commonly observed in spectra of circumstellar envelopes of evolved stars. The presence of rare isotopes indicates that the gas around CK Vul has been processed by nuclear burning of hydrogen and involved the CNO, and perhaps MgAl, cycles. However, the isotopic ratios we derived do not agree with yields predicted for any type of standard nucleosynthesis in stellar interiors nor with predictions of explosive nucleosynthesis of classical novae. The composition of the remnant is most bizarre and deepens the enigma of the nature of CK Vul.

3. A link to massive AGB stars

Surprisingly, the isotopic ratios we observationally constrained for CK Vul match extremely well the isotopic composition measured in the laboratory for a rare class of presolar SiC grains known as 'nova grains' (e.g. Liu et al. 2016; Nittler & Hoppe 2005). Although the origin of these grains remains unclear, the best explanation proposed so far appears to be a scenario where these grains are produced in nova runaway eruptions on a massive ONe white dwarf (e.g. Amari et al. 2001; José & Hernanz 2007). Rather than forming from pure nova ashes, these grains are thought to condense from material consisting in a few percent of nova-runaway products and in over 90 percent of solar-composition material that presumably comes from the non-degenerate companion. It is however uncertain

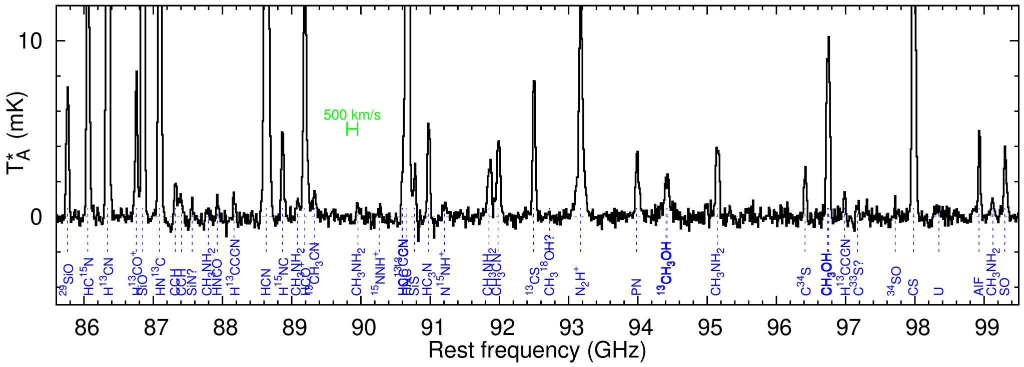

Fig. 1. Sample part of the spectrum of CK Vul obtained with the IRAM 30 m telescope. The millimeter-wave spectrum is exceptionally rich in emission lines of rare isotopologues.

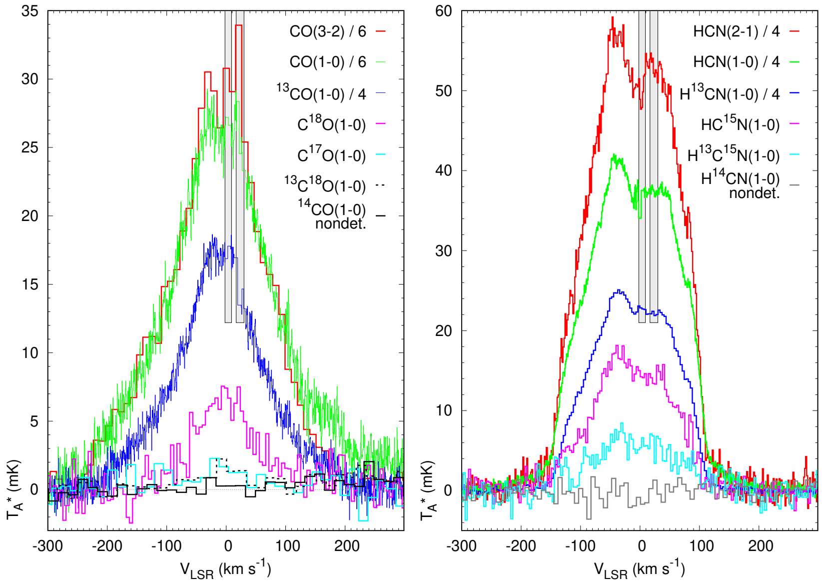

Fig. 2. Sample profiles of different isotopologues of CO and HCN observed with APEX and IRAM 30m. Note the presence of species consisting of two rare isotopes, such as $^{13}C^{18}O$ and $H^{13}C^{15}N$, which are very uncommon in stellar sources. By comparing lines of different isotopologues for a large number of different species, we calculated the isotopic ratios of the remnant.

if such systems would be able to produce SiC grains as they should be oxygen-rich environments. Nevertheless, models attempting to explain nova grains may in some aspects be adequate for CK Vul and suggest that a massive white dwarf or a NeO stellar core could have been involved in the 1670–72 eruption known as Nova 1670.

Detailed modeling is necessary to explore this potential link of CK Vul to the massive end of the asymptotic giant branch. One can consider different scenarios to explore in future. A nova eruption on a ONe white dwarf whose ashes would be diluted in solar-composition material, as proposed in Amari et al. (2001), is one possibility. It is however very unlikely scenario for CK Vul as it would require an enormous mass of nova-processed material. Also, it is highly unlikely that the system would produce such a rich molecular remnant as that observed around Nova 1670 (Kamiński et al. 2015). A stellar merger seems still a more attractive scenario. A violent stellar collision could have been directly responsible for disrupting a star that had a massive core and an envelope of nearly-solar elemental composition. The messy merger process could have dispersed material once forming the inner parts of the star and mix it with the material of the unprocessed envelope and of the disrupted companion (which presumably was of a much lower mass). There are no predictions whether such an event would result in any type of nucleosynthesis taking place during the merger event itself. Although detailed models would be most desired, future observations may also help to verify this highly speculative scenario.

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