Astronomical detection of radioactive molecule

$^{26}$AlF in the remnant of an ancient explosion

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Decades ago, $\gamma$-ray observatories identified diffuse Galactic emission at 1.809 MeV originating from $\beta^-$ decays of an isotope of aluminium, $^{26}$Al, that has a mean lifetime of 1.04 million years. Objects responsible for the production of this radioactive isotope have never been directly identified owing to insufficient angular resolutions and sensitivities of the $\gamma$-ray observatories. Here, we report observations of millimetre-wave rotational lines of the isotopologue of aluminium monofluoride that contains the radioactive isotope ($^{26}$AlF). The emission is observed towards CK Vul, which is thought to be a remnant of a stellar merger. Our constraints on the production of $^{26}$Al, combined with the estimates on the merger rate, make it unlikely that objects similar to CK Vul are major producers of Galactic $^{26}$Al. However, the observation may be a stepping stone for unambiguous identification of other Galactic sources of $^{26}$Al. Moreover, a high content of $^{26}$Al in the remnant indicates that, before the merger, the CK Vul system contained at least one solar-mass star that evolved to the red giant branch.

Historic records show that CK Vul or Nova 1670 underwent an unusual outburst in 1670–1672. It was similar to outbursts of objects known as red novae, which erupt in a stellar merger before cooling off to low temperatures. In this cool phase, they produce large amounts of molecular gas and dust. CK Vul was recently discovered to be associated with a significant amount of dust and molecular gas as well. What distinguishes CK Vul, even among red novae, is a high abundance of isotopes that are rare in matter of normal composition. In particular, our observation of $^{26}$AlF in four rotational transitions (Fig. 1 and Methods) is a firm detection of a radioactive molecule in CK Vul. This discovery follows numerous unsuccessful attempts to detect $^{26}$AlF in astronomical objects. The unstable nucleus of $^{26}$Al is virtually absent in solar-composition objects and has a modest abundance of $10^{-10}$ to $10^{-7}$ times less abundant than the stable isotope $^{27}$Al (Methods).

The molecular remnant of CK Vul was discovered at millimetre wavelengths in rotational emission lines from a large variety of molecules. Imaging has shown that the CO emission region has an extent of $\sim 13''$, a morphology of bipolar lobes and a torus-like feature, which are associated with a significant amount of dust and molecular gas as well. What distinguishes CK Vul, even among red novae, is a high abundance of isotopes that are rare in matter of normal composition. In particular, our observation of $^{26}$AlF in four rotational transitions (Fig. 1 and Methods) is a firm detection of a radioactive molecule in CK Vul. This discovery follows numerous unsuccessful attempts to detect $^{26}$AlF in astronomical objects. The unstable nucleus of $^{26}$Al is virtually absent in solar-composition objects and has a modest abundance of $10^{-10}$ to $10^{-7}$ times less abundant than the stable isotope $^{27}$Al (Methods).

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The 26Al isotope is produced in the Mg–Al cycle in hydrogen burning via the $^3$Mg$(p, \gamma)^{26}$Al reaction, which requires temperatures above $30 \times 10^8$ K. It is thought to be efficiently produced in a variety of stars, including: classical novae with O–Mg–Ne white dwarfs; Wolf–Rayet stars; core-collapse supernovae; and asymptotic giant branch (AGB) stars that experienced hot bottom burning. The progenitor of CK Vul was neither of these objects. However,
The helium core; therefore, there is no way to dredge 26Al up to the envelope convection never reaches is then deposited in a narrow outermost layer of the helium core for producing 26Al occur when a star develops a condensed degenerates; that is, for initial stellar masses 0.8–2.5 times 10^27 g of 26Al in the outermost layers of the helium core (that is, a factor of 1,000 more than that found in CK Vul). Given this result and other observational constrains, a merger of two low-mass stars with at least one being on the RGB is the most likely scenario to explain CK Vul. Population-synthesis studies indeed indicate that low-mass binaries evolving off the main sequence to the RGB (and with orbital periods of 1–30 d) have a high chance of merging.

The 26Al decays are followed by emission of energetic positrons, which may be an important local ionization source in CK Vul. Following Glassgold et al., our results suggest a 26Al-induced ionization rate of 2.0 × 10^{-16} s^{-1} per hydrogen nucleus for CK Vul. This is a lower limit considering that the derived 26Al mass is a lower limit and we adopted the solar elemental abundance for an object. The regions of strong emission in the two ions (N_2H^+ and HCO^+) that were observed in CK Vul simultaneously with AlF are more extended than that of 26AlF (Supplementary Fig. 1), suggesting that additional ionization mechanisms are active in the remnant. It is possible that atomic forms of the radioactive nuclide of aluminium extend and ionize the remnant beyond the region traced in 26AlF emission, or that other radioactive species are present in the remnant.

Fig. 1 | Spectra of rotational lines of AlF in CK Vul. Spectra are displayed in the local standard of rest (LSR) frame. a–j, Green vertical lines illustrate the hyperfine structure of the transitions (in arbitrary intensity units). Areas shaded in red and blue show the 27AlF (a–f) and 26AlF emissions (g–j), respectively, and represent the main emission region of AlF. Some spectra were smoothed in resolution, most heavily for 27AlF J = 1–0, which was observed with the Karl G. Jansky Very Large Array (VLA). The transition and telescope used to collect the data are indicated in each panel. For lines observed with a single-dish telescope and with an interferometer, only the interferometric spectrum is shown. In f, the 26Al 7–6 transition is contaminated by emission of methylamine, and a mirrored profile is shown with a dashed line to illustrate the contribution of 27AlF.

The feature shown with a black empty histogram was decomposed into two Gaussians corresponding to SO2 (red) and 26AlF (blue). The shaded grey histogram shows the best-fitting combined profile. Normalized profiles of unblended lines observed with interferometers are overlaid to illustrate their close alignment. Red lines correspond to transitions of 27AlF, while blue lines are for 26AlF.

More ordinary low-mass stars can produce 26Al as well. The 26Al synthesis takes place on the red giant branch (RGB) when hydrogen is burnt in a shell surrounding a helium core. Our model simulations (see ref. 24 and Methods) show that the most favourable conditions for producing 26Al occur when a star develops a condensed degenerate core; that is, for initial stellar masses 0.8–2.5M⊙. The 26Al isotope is then deposited in a narrow outermost layer of the helium core (Fig. 3). In a single RGB star, envelope convection never reaches the helium core; therefore, there is no way to dredge 26Al up to the stellar surface (and disperse it into the circumstellar and interstellar media). However, if the star is in a binary system and collides with a companion, matter from the interiors of both stars can be mixed and ejected into the circumstellar medium. In particular, if the companion has a condensed core, the 26Al-rich outer layers of the helium core of the RGB primary can be disrupted and exposed, to eventually form a remnant such as that of CK Vul. Only a small portion of the available 26Al would have to be dispersed to explain the observed mass of 26Al and the aluminium isotopic ratio measured in CK Vul. Our calculations show that stars of 0.8–2.5M⊙ store a few times 10^20 g of 26Al in the outermost layers of the helium core (that is, a factor of 1,000 more than that found in CK Vul). Given this...
From the intensity of the 1.8 MeV line, it was estimated that all Galactic sources produce $1\sim 3 M_\odot$ of $^{26}$Al every 1 Myr$\superscript{1,2,29}$. With our estimates of the $^{26}$Al mass in CK Vul, one would need $\sim 1,100$ mergers like CK Vul going off every year to explain the entire Galactic content of $^{26}$Al. This figure is unrealistic as current rates of red novae suggest one to two such energetic transients per decade$\superscript{18}$, and the rates are probably even lower for eruptions more characteristic of CK Vul$\superscript{1}$. In contrast, if the mass of $^{26}$Al in CK Vul is underestimated by a factor of 1,100—for example, by not accounting for $^{26}$Al present in the atomic phase, other molecules and solids—objects like CK Vul may be important contributors to the Galactic production of this radioactive nuclide. More observations and realistic models of the ionization and chemical structure of the remnant are necessary to investigate this issue further.

The 1.8 MeV emission arising from $^{26}$Al decays is hardly absorbed by interstellar or circumstellar matter$\superscript{12}$ and easily escapes from the compact $^{26}$AlF region, even though it is heavily obscured by dust and gas (Fig. 2). Using our $^{26}$AlF observational constraints as a lower limit on the $^{26}$Al content in CK Vul, we calculate that the $^{26}$Al decay line has a flux of $\gtrsim 1.6 \times 10^{18}$ cm$^{-2}$ s$^{-1}$, which is much below the sensitivity limit of the contemporary Spectrometer on INTEGRAL (SPI; $\sim 10^{-8}$ cm$^{-2}$ s$^{-1}$ in a 10$^5$ s integration$\superscript{19}$). At such low estimated flux, it will be challenging to detect the 1.8 MeV line from CK Vul, and probably from any other single stellar source, even with future more sensitive $\gamma$-ray instruments. However, the case of CK Vul illustrates that millimetre-wave spectroscopy performed by the Atacama Large Millimeter/submillimeter Array (ALMA) and Northern Extended Millimeter Array (NOEMA) can now be used to study Galactic sources of radioactive nuclides, provided they produce molecules. Modern interferometer arrays can not only detect but also spatially identify discrete objects that are actively enhancing the Galaxy in $^{26}$Al. Because observations of molecules yield relatively easily the isotopologue (and thus isotopic) ratios, which are not available through $\gamma$-ray observations, millimetre-wave spectroscopy also has the potential to better identify the nucleosynthesis processes that lead to the Galactic $^{26}$Al production.

**Methods**

**Spectroscopic data for AlF isotopologues.** The identification and analysis of the pure rotational emission of $^{26}$AlF and $^{27}$AlF was based on spectroscopic data prepared in this study. For $^{26}$AlF, we used mass-scaled Dunham parameters and hyperfine constants derived from laboratory measurements$\superscript{31}$. Accurate line positions of $^{26}$AlF were calculated through the mass-scaled Dunham parameters of $^{26}$AlF. We used fourth-order correction terms to derive positions of hyperfine components with an accuracy better than 1 MHz. The hyperfine splitting of $^{27}$AlF is more complex than that of $^{26}$AlF owing to a twice larger nuclear spin ($\hbar/2\pi=\frac{1}{2}$). To derive the hyperfine structure for $^{26}$AlF, we used higher-order Dunham corrections and scaled accordingly the $^{26}$Al electric quadrupole moment $Q$ and the magnetic coupling parameter $\mu$ with the nuclear $g$ factor. A permanent dipole moment of $\mu=1.53 D$ was adopted for both isotopologues. The spectroscopic constants we used to generate the line lists are given in Supplementary Table 1. Line frequencies, energies of the rotational levels above the ground ($E_J$), line strengths ($S_{J\ell}/\mu$) and partition functions were derived using goppher$\superscript{1}$. The method of our calculations is similar to that used in earlier studies of rotational spectra of $^{26}$Al$\superscript{12}$.

Spectroscopic laboratory studies of rare radioactive materials such as $^{26}$AlF would be very challenging. Although laboratory measurements are usually needed to unambiguously identify complex molecules, it is not necessary for simple diatomic species, especially for most astronomical applications. For diatomic molecules and within the Born–Oppenheimer approximation, the mass dependence of spectra can be separated from that of the bond length. The underlying theory was developed by Dunham in 1932$\superscript{2}$ and has been successfully applied to many molecules. The spectra of diatomic molecules of identical
The three 26AlF features (that is, level. All other lines are below our sensitivity limits. 

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sufficient to determine spectra of other isotopologues (for example, 26Al19F). High-

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The presence of 22AlF in CK Vul was revealed in the

interferometric observations. The following transitions were observed:

• The J = 1–0 transitions of 24AlF and 25AlF were covered but not detected. Their upper 5σ limits and the fluxes of the other detected lines are given in Supplementary Table 2.

Most of the corresponding transitions of 22AlF were also covered in the survey. We find a weak spectral feature at the expected location of 26AlF 3–2, but the emission line partially overlaps with a broader instrumental feature. The 3–4 line is also visible and it partially overlaps with the J = 3–2 line of SO (see below). Only rough flux constraints on the 24AlF 3–2 transition were obtained from this blending feature. The 4–5 transition of 26AlF overlaps with a much stronger line of CO J = 2–1 and its flux could not be reliably measured. Two other lines of 22AlF (that is, J = 8–7 and 9–8) were covered but not detected. Their upper 5σ limits and the fluxes of the other detected lines are given in Supplementary Table 2.

The following transitions were observed:

• The J = 1–0 transitions of 24AlF and 25AlF were covered by a Kₜ band spectrum obtained with the JVLA in the DnC configuration. The lowest transition of 25AlF has a significant hyperfine splitting that is comparable to the intrinsic line width of AlF emission (Fig. 1a). This extra broadening makes the line peak intensity lower and harder to detect than for lines at higher frequencies. Only after smoothing the spectrum to a resolution comparable to the hyperfine splitting is the emission of 24AlF 1–0 apparent (Fig. 1a). This transition should be considered as only tentatively detected. The flux of the line is at a 2σ level, which is insufficient to provide a good-quality map of the 24AlF 1–0 emission. To extract the spectrum, we used an aperture defined in maps of 25AlF 3–2 from NOEMA. The 24AlF 1–0 emission is not detected in the JVLA data, consistent with the isotopologue ratio derived in this study.

• The J = 3–2 transition of both AlF isotopologues was observed with the emerging NOEMA interferometer. Observations were obtained in 2016 and 2017 with seven and eight antennas, respectively. The WideX correlator was used. Both transitions are detected and their emission regions resolved with a beam of ~0.78 arcsec. At this angular resolution, the peak signal-to-noise values of the two emission regions are 24 and 5 (and higher for source-averaged fluxes).

• The J = 4–3 transitions were observed with six antennas of NOEMA and with WideX. The emission region is a beam of ~1.64 arcsec. The 25AlF emission may be contaminated by the HNCO 6ν₁–5ν₁ transition whose rest frequency is 29.7 km s⁻¹ away from that of 25AlF 4–3. The separation is smaller than the full width at half maximum of the observed feature of 40.8 km s⁻¹. An excitation model of HNCO based on the single-dish survey implies that less than 6% of the total flux of the observed feature may come from HNCO. However, the accuracy of this model is modest and it does not take into account the potential difference in spatial distributions of HNCO and AlF emission. The characteristics of the emission region ascribed here to 23AlF 4–3 are the same as those of other AlF transitions and do not indicate any sign of contamination. We therefore neglect the potential contribution from HNCO and interpret the total flux of the emission feature as that of 23AlF 4–3. The corresponding 25AlF 4–3 transition is detected by NOEMA but blends partially with the SO 50–120 MHz, and the predicted line positions are in excellent agreement with the centres of the molecular remnant and thus provided an important context for the interpretation of the AlF emission. The 25AlF 4–3 transition is consistent with that of 23AlF (see below). In the 4.75 GHz wide spectrum acquired with ALMA in Band 6, we observe only four features of similar intensity and width as those of 23AlF 7–6. Within the accuracy to which we can determine the observed line positions in CK Vul, the ALMA Band 6 spectrum indicates a probability of a chance coincidence of 1:840. A probability that 4 lines match the calculated frequencies is smaller than 10⁻⁹. Therefore, a false identification is highly unlikely.

All the interferometric data were calibrated using standard procedures. ALMA and NOEMA data were additionally self-calibrated on the strong continuum source. Continuum emission was subtracted from the visibilities as a zeroth- or first-order polynomial fitted to the full band and avoiding strong lines. Interferometric maps were obtained in CLEAN and using CLEAN. The weighting of visibilities—natural or robust—was adjusted to the aims of the analysis. We often used images with a restoring beam of a circular shape and of a diameter equal to the geometric mean of the ‘dirty’ beam size.
Excitation analysis and determination of the isotopic ratio. The excitation temperature and column densities of the AlF isotopologues were derived in a population-diagram analysis. The population diagram is shown in Supplementary Fig. 2. We used a Python code implementation of the Markov chain Monte Carlo method to obtain linear fits to the data. In the associated error analysis, we considered statistical uncertainties from the thermal noise in the flux measurements and 20% systematic errors in the flux calibrations. We assumed that both isotopologues are located in the same volume and have the same single excitation temperature. That the temperatures are, within uncertainties, equal for both species is evident from the same slopes of lines that can be fitted to both sets of points independently. The source size of 1.80 ± 0.84 arcsec was used to calculate the beam filling factors. This size is a weighted mean of all beam-deconvolved sizes measured in our 26AlF and 27AlF maps. Free parameters of the population-diagram fit were the excitation temperature \( T_e \), column density of 26AlF \( N_{26} \), and ratio of the column density of 27AlF to that of 26AlF \( N_{27}/N_{26} \). We used uniform (‘uninformative’) priors for the three parameters, allowing their values to be in arbitrary but reasonably broad ranges. A few thousand ‘walkers’ were used in emcee to derive the posterior distributions. After the first determination of the column densities, we calculated the line opacities and corrected the measured fluxes for the corresponding systematic free parameters. The calculation was then repeated. The maximum optical thickness in this second iteration was \( \tau_{max} = 0.3 \). The saturation correction is only 1.4% higher than in the previous iteration and no further corrections were applied. The procedure yielded \( T_e = 12.9^{+3.0}_{-2.4} \) K, \( N_{26} = 3.0^{+0.9}_{-0.7} \times 10^{12} \) cm\(^{-2} \) and \( N_{27}/N_{26} = 7.9^{+1.8}_{-1.1} \), where the median values are associated with corresponding 97.3% confidence levels. These uncertainties are underestimated and do not take into account, for instance, errors in the source size.

The population-diagram analysis relies on the assumption of thermodynamic equilibrium in the gas. The assumption is not granted in CK Vul considering that some species appear to be subthermally excited. However, the AlF population diagram itself does not produce any strong indications from what is expected in thermodynamic equilibrium. Also, the excitation temperature of AlF derived here is consistent with the kinetic temperature constrained from the single-dish survey. Using collision rates of AlF with para-H\(_2\) and with helium at 10 K\(^{-6}\), we calculated critical densities for all observed transitions. They range from 10\(^4\) cm\(^{-3}\) for \( J = 1 \rightarrow 0 \) to 10\(^7\) cm\(^{-3}\) for \( J = 7 \rightarrow 6 \) and are therefore comparable to critical densities of analogous transitions of low-density molecular tracers such as CO. The AlF gas is probably thermalized and the level populations are probably close to thermodynamic equilibrium.

**Nucleosynthesis of Al.** To investigate the synthesis of 26Al in low-mass stars evolving off the main sequence to RGB, we analysed state-of-the-art solar-metallicity evolutionary sequences calculated with the Monash stellar-evolution code. The surface abundances on the AGB were investigated with the code described in ref. \(^\text{[1]}\). The models are evolved from the zero-age main sequence to near the end of the thermally pulsing AGB phase. For the purposes of this study, we sampled the interior composition of the star at the tip of the RGB before core helium burning is ignited. The grid includes models between 1 and 8\( \odot \) and we considered models for 1–3\( \odot \) for this study. The nuclear network and initial abundances used were calculated critical densities for all observed transitions. They range from 10\(^4\) cm\(^{-3}\) for \( J = 1 \rightarrow 0 \) to 10\(^7\) cm\(^{-3}\) for \( J = 7 \rightarrow 6 \) and are therefore comparable to critical densities of analogous transitions of low-density molecular tracers such as CO.

The AlF gas is probably thermalized and the level populations are probably close to thermodynamic equilibrium.

Data availability. Raw and processed ALMA data that support the findings of this study are accessible in the ALMA archive (http://almascience.nrao.edu/asq). These and other astronomical data are also available from the corresponding author upon reasonable request. The electronic table containing the calculated hyperfine structure of 26Al transitions is available at CDS: http://cdsarc.u-strasbg.fr/viz-bin/cat?/other/NaTAS.

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35. Dunham, J. L. The energy levels of a rotating vibrator. *Phys. Rev.* **41**, 721–731 (1932).
36. Lutz, J. J. & Hutson, J. M. Deviations from Born–Oppenheimer mass scaling in spectroscopy and ultracold molecular physics. *J. Mol. Spectrosc.* **330**, 43–56 (2016).
37. McMullin, J. P., Waters, B., Schiebel, D., Young, W. & Golap, K. CASA architecture and applications. In *Astronomical Data Analysis Software and Systems XVI* (eds Shaw, R. A., Hill, F. & Bell, D. J.) 376 (Conference Series Volume 127, Astronomical Society of the Pacific, 2007).
38. Goodman, J. & Weare, J. Ensemble samplers with affine invariance. *Commun. Appl. Math. Comput. Sci.* **5**, 65–80 (2010).
39. Foreman-Mackey, D. et al. emcee: the MCMC hammer. *Publ. Astron. Soc. Pac.* **125**, 306 (2013).
40. Goldsmith, P. F. & Langer, W. D. Population diagram analysis of molecular line emission. *Astrophys. J.* **517**, 209–225 (1999).
41. Gotoum, N., Hammami, K., Owono Owono, L. C. & Jaidane, N.-E. Collision induced rotational excitation of AlF (X1Σ+1) by para-H2 (j = 0). *Astrophys. Space Sci.* **337**, 553–561 (2011).
42. Gotoum, N. et al. Rotational excitation of aluminium monofluoride (AlF) by He atom at low temperature. *Astrophys. Space Sci.* **332**, 209–217 (2010).
43. Lattanzio, J. C. The asymptotic giant branch evolution of 1.0–3.0 solar mass stars as a function of mass and composition. *Astrophys. J.* **311**, 708 (1986).
44. Karakas, A. I. Helium enrichment and carbon-star production in metal-rich populations. *Mon. Not. R. Astron. Soc.* **445**, 347–358 (2014).
45. Young, P. A. et al. Observational tests and predictive stellar evolution. *Astrophys. J.* **556**, 230 (2001).

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**Author contributions**

T.K. wrote the text and analysed the observations. A.A.B. and T.F.G. prepared the spectroscopic data. J.M.W. prepared, executed and calibrated the NOEMA observations. K.T.W. prepared and reduced the JVLA observations. T.K. prepared and reduced the ALMA and all single-dish observations. N.A.P. prepared and calibrated the SMA observations. R.T. and A.K. ran stellar-evolution models. All authors contributed to the interpretation of the data.

**Competing interests**

The authors declare no competing interests.

**Additional information**

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