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The unpolarized macronova associated with the gravitational wave event GW 170817

S. Covino[1*], K. Wiersema[2], Y. Z. Fan[3], K. Toma[4,5], A. B. Higgins[2], A. Melandri[1], P. D'Avanzo[1], C. G. Mundell[6], E. Palazzi[7], N. R. Tanvir[2], M. G. Bernardini[1,8], M. Branchesi[9,10], E. Brocato[11], S. Campana[1], S. di Serego Alighieri[12], D. Götz[13], J. P. U. Fynbo[14], W. Gao[1,15], A. Gomboc[16], B. Gompertz[17], J. Greiner[18], J. Hjorth[14], Z. P. Jin[3], L. Kaper[19], S. Klose[20], S. Kobayashi[21], D. Kopac[22], C. Kouveliotou[27], A. J. Levan[23], J. Mao[24], D. Malesani[14], E. Pian[7], A. Rossi[7], R. Salvaterra[25], R. L. C. Starling[2], I. Steele[21], G. Tagliaferri[1], E. Troja[26], A. J. van der Horst[27,28] and R. A. M. J. Wijers[19]

The merger of two dense stellar remnants including at least one neutron star is predicted to produce gravitational waves (GWs) and short-duration gamma ray bursts[1,2]. In the process, neutron-rich material is ejected from the system and heavy elements are synthesized by r-process nucleosynthesis[1,3]. The radioactive decay of these heavy elements produces additional transient radiation termed kilonova or macronova[4–10]. We report the detection of linear optical polarization, $P=(0.50\pm0.07)\%$, 1.46 days after detection of the GWs from GW 170817—a double neutron star merger associated with an optical macronova counterpart and a short gamma ray burst[11–14]. The optical emission from a macronova is expected to be characterized by a blue, rapidly decaying component and a red, more slowly evolving component due to material rich in heavy elements—the lanthanides[15]. The polarization measurement was made when the macronova was still in its blue phase, during which there was an important contribution from a lanthanide-free outflow. The low degree of polarization is consistent with intrinsically unpolarized emission scattered by galactic dust, suggesting a symmetric geometry of the emitting region and low inclination of the merger system. Stringent upper limits to the polarization degree from 2.45–9.48 days post-burst are consistent with the lanthanides-rich macronova interpretation.

The search for the optical counterpart to gravitational wave (GW) 170817[11] quickly allowed the discovery of the possible counterpart, named AT2017gfo (also known as SSS17a), in the outskirts of the elliptical galaxy NGC4993 at about 40 Mpc[14]. Spectroscopic observations showed that this source was highly unusual and probably associated with the GW event and a short gamma ray burst (GRB)[16]. Only a few possible detections of macronova emission have been reported in the literature and in all of these studies the temporal and spectral evolution of the afterglows of on-axis short GRBs was analysed[17–20]. GRB 170817 A is intrinsically the weakest short GRB detected so far, which may be a regular short GRB but viewed from an off-axis orientation. The off-axis scenario is also helpful in reconciling the probability of GW–GRB association for this event[21,22]. Therefore SSS17a offers a unique opportunity to study a macronova emission plausibly not polluted by the GRB emission. The combination of a likely off-axis jet and the potential ability of Laser Interferometer Gravitational-Wave Observatory/Virgo data to constrain the merger geometry and orientation gave great urgency to a polarimetric measurement of the symmetry and orientation of the optical emission region(s) post-merger. Measuring the degree of polarization of the electromagnetic emission provides unique constraints on the geometry of the system and the properties of any incipient magnetic fields[23,24].

[1]Istituto Nazionale di Astrofisica / Brera Astronomical Observatory, via Bianchi 46, 23807 Merate (LC), Italy. [2]Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK. [3]Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China. [4]Frontier Research Institute for Interdisciplinary Sciences, Tohoku University, Sendai 980-8578, Japan. [5]Astronomical Institute, Tohoku University, Sendai 980-8578, Japan. [6]Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, UK. [7]Istituto Nazionale di Astrofisica / Istituto di Astrofisica Spaziale e Fisica Cosmica di Bologna, Via Gobetti 101, 40129 Bologna, Italy. [8]Laboratoire Univers et Particules de Montpellier, Université de Montpellier, Centre National de la Recherche Scientifique / IN2P3, Montpellier 34095, France. [9]Gran Sasso Science Institute, 67100 L'Aquila, Italy. [10]Istituto Nazionale di Fisica Nucleare / Laboratori Nazionali del Gran Sasso, 67100 L'Aquila, Italy. [11]Istituto Nazionale di Astrofisica / Osservatorio Astronomico di Roma, Via di Frascati, 33, 00078 Monteporzio Catone, Italy. [12]Istituto Nazionale di Astrofisica / Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125 Firenze, Italy. [13]Commissariat à l'Énergie Atomique Saclay—Direction de la Recherche Fondamentale/Irfu/Dèpartement d'Astrophysique, 91191 Gif-sur-Yvette, France. [14]Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, 2100 Copenhagen, Denmark. [15]Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing 210046, China. [16]Centre for Astrophysics and Cosmology, University of Nova Gorica, Vipavska 11c, 5270 Ajdovščina, Slovenia. [17]Space Telescope Science Institute, Baltimore, MD 21218, USA. [18]Max-Planck-Institut für extraterrestrische Physik, Giessenbachstr. 1, 85748 Garching, Germany. [19]Anton Pannekoek Institute, University of Amsterdam, Science Park 904, 1098XH Amsterdam, The Netherlands. [20]Thüringer Landessternwarte Tautenburg, Sternwarte 5, 07778 Tautenburg, Germany. [21]Astrophysics Research Institute, Liverpool John Moores University, ic2, Liverpool Science Park, 146 Brownlow Hill, Liverpool L3 5RF, UK. [22]Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia. [23]Department of Physics, University of Warwick, Coventry CV4 7AL, UK. [24]Yunnan Observatories, Chinese Academy of Sciences, 650011 Kunming, Yunnan Province, China. [25]Istituto Nazionale di Astrofisica / Istituto di Astrofisica Spaziale e Fisica Cosmica Milano, via E. Bassini 15, 20133 Milano, Italy. [26]Department of Astronomy, University of Maryland, College Park, MD 20742, USA. [27]Department of Physics, The George Washington University, 725 21st Street NW, Washington, DC 20052, USA. [28]Astronomy, Physics, and Statistics Institute of Sciences, Washington, DC 20052, USA. *e-mail: stefano.covino@brera.inaf.it

Our linear polarimetry campaign consisted of a set of five observations carried out with the European Southern Observatory Very Large Telescope equipped with the FOcal Reducer and low dispersion Spectrograph (FORS2; http://www.eso.org/sci/facilities/paranal/instruments/fors.html) starting on 18 August 2017 and spanning almost ten days. After that, the transient was too faint for a reliable polarimetric analysis. Details of the observing setup, data reduction and analysis are reported in the Methods. The derived degree of linear polarization, position angle and optical brightness after instrumental corrections had been applied are given in Table 1. A complete observation log, including the dates of the observations, exposure times, filters and seeings, is reported in Table 2. The Stokes parameters for optical transient and nearby field stars for the first four epochs are shown in Fig. 1. Over the duration of our campaign, the transient showed a degree of linear polarization and a position angle fully consistent with that shown by stars in the field whose polarization is induced by dust in our Galaxy. This implies that the macronova emission is essentially unpolarized at a level driven by the photometric uncertainties and the spread of polarization shown by field stars (that is, 0.4–0.5%).

GW 170817 originated in the coalescence of two neutron stars[11]. Numerical simulations show that these events can eject a small part of the original system into the interstellar medium[3,25,26] and also form a centrifugally supported disk that is quickly dispersed in space with a neutron-rich wind[7]. These two different ejection mechanisms are characterized by material of differing composition. The outflows from the disk are probably lanthanide free since the synthesis of heavier elements is suppressed by the high temperature[8], while the surface material is the site of an intense r-process nucleosythesis, producing heavy elements. In both cases, the spectrum should be close to a black-body, peaking in the optical in the disk-wind case and in the infrared for the lanthanide-rich material due to its very large opacity[8,9]. Ejecta should flow out anisotropically around the orbital plane of the system and outflows in the polar region can be produced by a strong shock driven by the merger and by processes such as viscous heating and magnetic effects in the disk[27]. Anisotropies induced by electron scattering can then produce some polarization[28]. As pointed out by Kiuchi at al.[27], in the case of high optical depth to electron scattering (~1) and assuming spectral lines do not significantly depolarize the global emission, the linear polarization observed from the equatorial plane could be as high as a few percent. As is the case of supernovae, this depends on the degree of asymmetry of the photosphere. However, with respect to the supernova case, if the ejecta are mainly composed of r-process elements, the ionization degree is not particularly high[7,29]

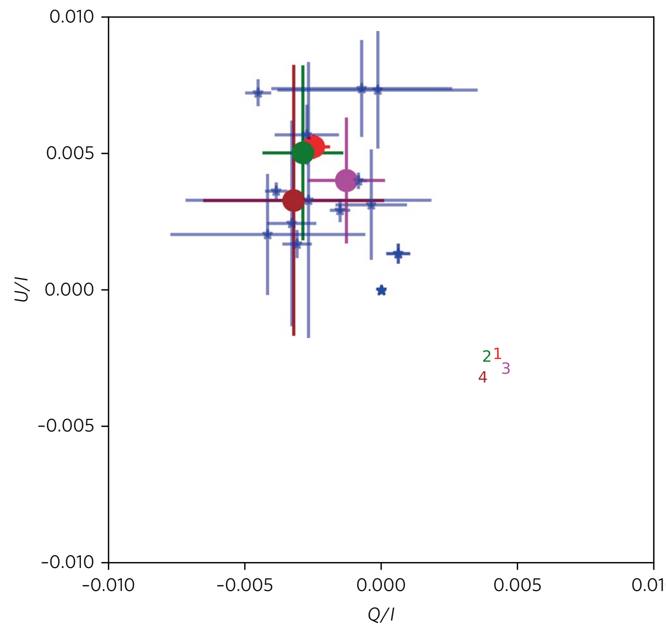

Fig. 1 | *Q/U* Stokes parameter plot for the optical transient and several field stars near to the transient. The reported numbers in the plot indicate the observation run as in Table 2. The polarization of AT2017gfo (circles) is essentially indistinguishable from that shown by field stars (blue stars). Errors are at 1σ. The Stokes parameters are a set of four parameters that describe the full polarization state of electromagnetic radiation. *Q* measures the difference between radiation intensity in the horizontal and vertical direction of a given reference frame, whereas *U* measures the difference between directions inclined by 45° and 135° with respect to the reference frame. *I* is the total intensity of the radiation. Together, *Q* and *U* therefore give the amplitude and angle of the linearly polarized component of the received intensity.

Table 1 | Results of the polarimetric campaign

$T - T_{GW}$ (days)	Q/I	U/I	Polarization (%)	Position angle (deg)	Magnitude (AB)
1.46	−0.0021 ± 0.0008	+0.0046 ± 0.0007	0.50 ± 0.07	57 ± 4	17.69 ± 0.02
2.45	−0.0025 ± 0.0016	+0.0044 ± 0.0032	<0.58	-	18.77 ± 0.04
3.47	−0.0009 ± 0.0015	+0.0034 ± 0.0024	<0.46	-	19.27 ± 0.01
5.46	−0.0029 ± 0.0033	+0.0026 ± 0.0050	<0.84	-	20.39 ± 0.03
9.48	+0.0412 ± 0.0216	−0.0095 ± 0.0126	<4.2	-	20.69 ± 0.11

Columns report the time after the GW event (17 August 2017, 12:41:04 UT; refs [11,13]), the *Q/I* and *U/I* Stokes parameters are corrected for the instrumental polarization, the bias-corrected polarization[34], the position angle and the magnitude obtained by the acquisition frames corrected for the galactic extinction. Errors are at 1σ and upper limits are given at the 95% confidence level.

Table 2 | Observation log

Run	Day (August 2017, UT)	Exposure time (s)	Filter	Seeing (arcsec)	Airmass	Sun altitude (deg)
1	18.965–19.017	60	$R_{special}$	0.7–1.0	1.36–1.96	10.8–27.7
2	19.967–19.996	90	$R_{special}$	1.5–2.0	1.39–1.68	11.4–20.9
3	20.975–21.017	90	$R_{special}$	0.7–1.0	1.48–2.05	13.8–27.3
4	22.973–23.018	120	$R_{special}$	0.7–1.0	1.51–2.20	13.0–27.7
5	26.992–27.027	300	z	0.7–1.0	1.91–2.80	19.2–30.2

Columns report the run number, observation dates, filter, observed seeing, airmass of the target and Sun altitude below the horizon.

and the number density of free electrons is proportionally lower. With typical parameters, the electron scattering opacity is lower than the total opacity ($\kappa \sim 10^2\,\mathrm{cm}^2\,\mathrm{g}^{-1}$) by three orders of magnitude and the expected linear polarization is reduced by a similar factor compared with the electron-scattering dominant case[28].

The emission from the wind could instead have a different composition and be more similar to typical supernova ejecta. A blue component was identified in the spectra of AT2017gfo[16] and it showed a more rapid evolution than the redder component. The emission from the lanthanide-rich material is not expected to display any detectable linear polarization, but the situation can be significantly different for the early emission phase that is dominated by the lanthanide-free material, for which the temperature is higher (as is the ionization degree) and the electron scattering optical depth is ~1. Assuming that at our first epoch the blue component was at least as important as the lanthanide-rich emission, we can derive an upper limit of ~1% on the polarization of the lanthanide-free component. The low gamma-ray luminosity of GRB 170817 A[12,13], despite its location in the local Universe, seems to indicate that it is an off-axis event, although the possiblity of a peculiarly weak event cannot be ruled out. A natural prediction of the off-axis scenario is that, following the deceleration of the outflow, the afterglow emission will be visible for the observer at very late times[2]. Although the off-axis afterglow emission could be linearly polarized[30], during our polarimetric observations there was no evidence for such a component in the optical bands[16]. The absence of polarization in our late-time optical data is therefore quite natural, while at earlier times the limits on the polarization of the lanthanide-free component are still within the allowed possibilities since the actual polarization fraction also depends on the degree of asymmetry of the outflows. This would be different in the case of a neutron star–black-hole merging, since we would expect the ejecta to be much more anisotropic than in the neutron star–neutron star case[15,28].

Our non-detection of linear polarization, which was unambiguously due to a macronova emission up to very stringent limits, is thus consistent with the theoretical expectations[28] for this category of sources. It also strengthens the identification of AT2017gfo with a macronova resulting from a neutron star–neutron star coalescence associated with a short GRB and a GW event, and indirectly confirms that these sources are the site of r-process production. If these events are fairly common even in the local Universe[22], it is likely that in the near future more macronovae will be observed enabling the exploration of a variety of merging conditions and system parameters such as viewing angles, mass ratios, possible off-axis afterglows, and so on. A spectro-polarimetric coverage that tracks the evolution of the phenomenon will shed light on possible deviations from the main expectations that are inaccessible with other techniques.

Methods

Our target, AT2017gfo, is the optical counterpart of the first GW signal detected by the Advanced Laser Interferometer Gravitational-Wave Observatory and Virgo network[31,32] from the merger of a binary system of neutron stars, GW 170817. Data were in general of excellent quality and were reduced following standard methods (that is, frames were bias-corrected and flat fielded, and bad pixels were flagged). Photometric analysis was carried out with standard aperture photometry. An additional complication arose since the target is located in the outskirts (at ~10 arcsec) of the bright galaxy NGC 4993 and for the latest epochs the galaxy light was comparable or more intense than the SSS17a brightness. We therefore modelled the external part of the galaxy with an analytical profile and effectively removed its contribution at the transient position. Photometry for the target was obtained by the acquisition frames calibrating with objects in the same field of view with the Pan-STARRS1 data archive (https://panstarrs.stsci.edu). Polarimetric observations were carried out using a Wollaston prism to split the image of each object in the field into two orthogonal polarization components that appeared in adjacent areas of the detector. A mask was used to avoid overlap of the two component images. For each position angle $\varphi/2$ of the half-wave plate rotator, we obtained two simultaneous images of cross-polarization at angles φ and $\varphi + 90°$. We obtained observations at position angles 0, 22.5, 45 and 67.5° of the half-wave plate. This technique allowed us to remove any differences between the two optical paths (ordinary and extraordinary ray), including the effects of seeing and airmass changes. It was also possible to estimate the polarization introduced by galactic interstellar grains along the line of sight by studying the polarization of a large number of stars in the same detector area of the target to avoid a possible dependence of the instrumental polarization on the field of view position. The optical extinction in our Galaxy is $A_V \sim 0.3$ mag and there is negligible extinction in the host galaxy[16]. This implies that dust-induced polarization up to almost 1% would be possible[33], although these are only statistical estimates and large variations on the main trend may be expected. The weighted average polarization shown by a set of stars near the transient turned out to be $P \sim 0.35\%$ with a position angle $PA \sim 56°$. Polarization is a positive quantity. At a low signal-to-noise ratio it suffers from a statistical bias, which was properly corrected[34]. The last observation in the z-band did not allow us to derive constraining results because of the increasing difficulties due to the fading of the counterpart and the rapidly reducing visibility window. With the same setup we also observed polarized and unpolarized standard stars to convert position angles from the telescope to the celestial reference frame, and to correct for the small instrumental polarization introduced by the telescope. More details on the imaging polarimetric data analysis can be found in ref. [35].

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

All authors contributed to the work presented in this paper. S.C. and K.W. coordinated the data acquisition, analysed the data and wrote the paper. A.B.H., A.M., P.D., E.P. and N.T. contributed to the data analysis. Y.F. and K.T. contributed to the theoretical discussion. C.M.M. contributed to the writing of the paper.

Competing interests

The authors declare no competing financial interests.

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