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Shedding Light on the Geometry of Kilonovae

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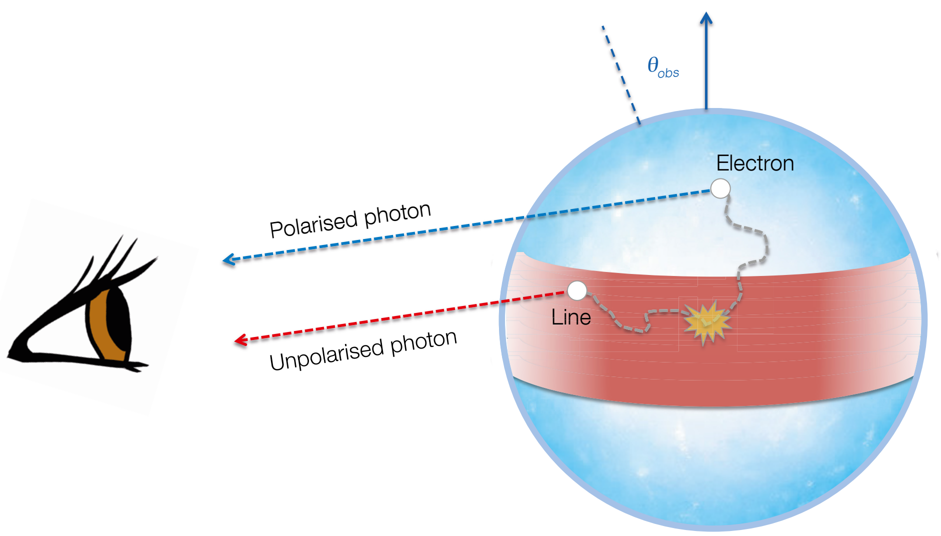
We present the first results of a campaign aimed at characterising the linear polarisation signals and thus the geometry of binary neutron star mergers (i.e., kilonovae). We carried out the first polarimetric observations of a kilonova called AT 2017gfo, using the FOcal Reducer/low dispersion Spectrograph 2 (FORS2). We predicted for the first time the polarisation signatures expected from kilonovae and highlighted the best strategy to detect linear polarisation in future events. Our studies demonstrate how the detection of polarisation will constrain crucial parameters of these systems, such as the inclination and composition, distribution and extent of the different components of the ejecta.

The first discovery (Abbott et al., 2017) of both a gravitational wave source GW170817 and its electromagnetic counterpart AT 2017gfo[a] marked year zero of the multi-messenger gravitational-wave era, and has been the subject of about 500 articles posted on the preprint server arXiv[1] in the past year. The gravitational wave was generated by the merger of two neutron stars and gave rise to an electromagnetic transient — called a kilonova — which was intensively monitored with all the main ground-based and space-borne facilities. This single event provided the smoking gun for a number of unresolved discussions, for example, on the nature of short gamma-ray bursts and the origin of *r*-process elements in the Universe.

Despite the general agreement between existing models and data, some crucial ingredients are still missing. State-of-the-art simulations and the analysis of AT 2017gfo suggest that the material ejected in kilonovae is likely to be distributed in two distinct components (see cartoon in Figure 1): a component around the merger plane that is relatively faint and red — characterised by the presence of heavy elements (including lanthanides with high opacities) — and a relatively bright and blue component at higher latitudes, characterised by relatively light elements. However, critical parameters of the system like inclination, mass, velocity, and composition and distribution of the ejecta components are still uncertain despite their being crucial, for example, in the estimation of kilonova rates, the comparison of yields to cosmic abundances, and the derivation of the Hubble constant. This is where polarimetry can come to the rescue.

Polarisation is sometimes an unsettling quantity to think about as, unlike the other two and more familiar properties of light — brightness and colour — it is almost impossible to observe with the naked eye. It is, however, an extremely powerful tool for studying the geometry of extragalactic sources such as kilonovae, which are otherwise too far away to be spatially resolved using other imaging techniques. Radiation from kilonovae can be linearly polarised by electron scattering, or depolarised by interactions with atoms. Linear polarimetry is thus sensitive to the geometry of the ejecta, the distribution of elements within

Figure 1. A cartoon illustrating the origin of polarisation in kilonovae. Photons escaping the ejected material from the red component are preferentially depolarised by line interactions, while those leaving the ejecta from the blue component are more likely to be polarised by electron scattering. These both contribute to the total polarisation signal that could be observed in future kilonova events.



the ejecta, and the interplay between different sources of opacity. This allows us to study properties that are not easily constrained through the analysis of photometric light curves and spectra alone.

Polarisation of AT 2017gfo

We presented polarimetric data of AT 2017gfo taken with FORS2 in Covino et al. (2017). Five epochs were secured, spanning a range between about 1.5 and 10 days after the binary neutron star merger. A polarisation signal of $P = 0.50 \pm 0.07\%$ and a polarisation angle, PA = $57° \pm 4°$ were measured during the first observation. Stringent upper limits were placed on the following epochs, all consistent with the former measurement.

Despite the detection of a polarisation signal in the first epoch, determining what fraction of this is intrinsic to the kilonova and what fraction is due to polarisation induced by dust along the line of sight is not trivial. In fact, the polarisation percentage and angle observed for AT 2017gfo are both consistent with those shown by several stars in the field of view. This suggests that a good fraction of the signal detected is due to dust in our galaxy, and that the intrinsic emission was therefore weakly polarised.

The origin of polarisation in kilonovae

In a follow-up paper, we predict the polarisation signal expected from a kilonova for the first time, and identify the best strategy to constrain important parameters of the system in future polarimetric observations (Bulla et al., 2018). We focus on the optical emission, as this is where kilonovae are brightest and thus most easily detectable using ESO facilities.

As illustrated in Figure 1, our work demonstrates that the presence of two separate ejecta components gives rise to a detectable polarisation signal in kilonovae. While photons coming from the red component are typically depolarised by interactions with atoms, photons from the blue component are preferentially scattered off, and polarised by, electrons. This leads to a net polarisation signal that can reach ~ 1% levels for favourable inclinations of the system (i.e., for an equatorial viewing angle; see Figure 2).

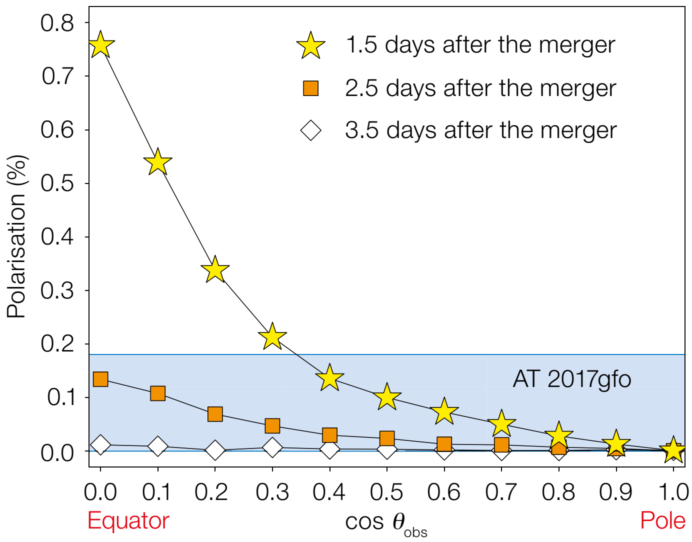


Figure 2. Polarisation predicted by our simulations as a function of the observer orientation, from the equator ($\cos\theta_{obs} = 0$) to the pole ($\cos\theta_{obs} = 1$). Different symbols correspond to different epochs after the merger of two neutron stars. The blue shaded area marks the range of polarisation estimated for AT 2017gfo.

Our simulations predict that the polarisation signal should reach a maximum at around 7000 Å and become negligible about two or three days after the merger for all observer orientations. These predictions are crucial for planning future polarimetric campaigns, highlighting that early (within two days of the event) observations around 7000 Å are required to detect polarisation in kilonovae.

Our modelling also suggests that any signal observed after three days would not be intrinsic (see white diamonds in Figure 2) but rather due to intervening interstellar dust. Since dust polarisation is constant with time, this provides a simple way to characterise the interstellar signal from late-time polarimetry and remove it from the polarisation intrinsic to the kilonova detected earlier. In the case of AT 2017gfo, we estimated the interstellar polarisation to be $0.49 \pm 0.05\%$, leading to an upper limit on the intrinsic polarisation of $P < 0.18\%$ (see shaded area in Figure 2). The better handle on the intrinsic signal of AT 2017gfo allows us to constrain the inclination of the system to within 60° of the polar direction ($\cos\theta_{obs} \geq 0.4$, see Figure 2), a value which is consistent with independent measurements from the literature.

Although the polarisation signal is consistent with zero (i.e., unpolarised) in this particular event, the detection of non-zero polarisation in future kilonovae will unambiguously reveal the presence of a lanthanide-free blue component of the ejecta. Because of the competition between polarising radiation from the blue component and depolarising radiation from the red component, the polarisation signal is predicted to be strongly dependent on the relative extent of the ejecta components for inclinations close to the merger plane. The detection of a polarisation signal in future events at favourable orientations will therefore place constraints on the spatial and angular distribution of the two ejecta components.

A bright future ahead

In these studies, we have: (i) established the origin of polarisation in kilonovae; (ii) made quantitative predictions about the polarisation signal as a function of observer orientation and time; (iii) highlighted the best strategy to drive a future polarimetric observing campaign; (iv) identified a simple approach to estimate the interstellar polarisation from late-time observations and thus to disentangle the intrinsic and interstellar signals from earlier epochs; (v) constrained the system inclination of AT 2017gfo; and (vi) demonstrated how the detection of polarisation in future kilonova events can unveil the spatial extent of the two ejecta components.

The best is yet to come! LIGO, the Laser Interferometer Gravitational-Wave

Observatory and the Virgo interferometer will begin taking data again in a couple of months, discovering many more kilonovae that we could follow up with polarimetry. The flexibility and reliability of ESO facilities is a strong factor in this exciting and innovative quest.

The detection of polarisation in future kilonova events, coupled to the predictions made by our modelling, will unambiguously reveal the presence of a lanthanide-free blue component and allow us to constrain important parameters like the geometry of the ejecta components and the inclination of the system.

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References

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Links

[1] The astrophysics arXiv preprint server: https://arxiv.org/archive/astro-ph

Notes

[a] The name of the kilonova AT 2017gfo was assigned by the Transient Name Server, the official IAU server through which new astronomical transients are reported.

V. Forchi/ESO

Unit Telescope 1 (called Antu) hosts FORS2, probably the most versatile instrument at the VLT.