Making Sense of Nothing

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A model of the optical light detected following the merger of two neutron stars reveals polarization to be a unique probe of the geometry of the kilonova explosion that accompanied the gravitational waves.

At precisely 12:41:06 UTC on 17 August 2017, a watershed moment in the history of astronomy occurred when electromagnetic radiation – photons of light – were received from the same astronomical source which, 1.7 seconds earlier, had triggered a gravitational wave detection¹. Dubbed AT 2017gfo (or, alternatively, GW170817 or GRB 170817A), the gravitational and electromagnetic messengers came courtesy of two stellar corpses – neutron stars – spiraling together to generate a “kilonova”, rippling the fabric of space and generating electromagnetic fireworks spanning from radio waves to gamma rays. In one of astronomy’s worst-kept secrets, news of the unprecedented detections and ensuing festival of followup observations was withheld until 16 October 2017, when an avalanche of papers simultaneously appeared on the astronomy preprint archive (http://arxiv.org/archive/astro-ph), officially heralding the birth of "multi-messenger" astronomy. Writing in Nature Astronomy, Mattia Bulla et al.² take a first crack at extracting quantitative meaning from a curious null result announced on that day: The optical light of the kilonova was unpolarized³.

That it has taken a full year for a theoretical paper to plumb the expected polarization properties of kilonova light reminds us that astronomical polarimetry is a tricky business. The observations are challenging, the data reduction tedious and prone to false-positives, and the analysis and ultimate conclusions frequently open to discordant interpretation. Yet for all the complexity, the potential windfall is enormous: Polarimetry can reveal the geometry of unresolvable astronomical sources (that is, those that remain “point-like” in our sky, certainly true for AT 2017gfo at a distance of roughly 130 million light years⁴). Such information is generally beyond the reach of any other technique.
Here is the essential idea. The hot, expanding ejected material of just about any type of stellar explosion (nova, supernova, kilonova, etc.) contains an abundance of free electrons at early times, which very effectively scatter – and polarize – light. That is, the oscillating electric and magnetic fields associated with each photon of the light, normally oriented in random directions (unpolarized), become lined up (polarized) by the scattering process. Indeed, if we could spatially resolve such an object, we would expect to measure changes in both the direction and strength of the polarization as a function of position in the scattering “atmosphere”. For an unresolved spherical source (or, more generally, a source that presents circular symmetry in the plane of the sky), however, the directional components of the polarization cancel exactly, and yield zero net polarization (Fig. 1a). If, however, the source has regions of its electron-scattering atmosphere blocked by obscuring material, incomplete cancellation occurs, and a net polarization results (Fig. 1b). Determining how much polarization is to be expected is the job of the theoretical modeler, and will in general be a strong function of the assumed initial physical conditions, how these conditions evolve with time, and the viewing orientation to the system.

In the first polarimetry data ever reported for a kilonova, Covino et al. present five measurements of AT 2017gfo sampling from 1.46 to 9.48 days after the neutron-star merger. All epochs yielded no intrinsic polarization to varying degrees of statistical significance. Naively, such null results would seem to admit two possibilities: (1) An unobscured view of a circularly-symmetric electron-scattering atmosphere (Fig. 1a); or (2) an atmosphere in which the photons are not being predominantly scattered by – and, hence, polarized by – free electrons. To sort out which is at work, Bulla et al. undertake the first complete computational modeling of the polarization expected for early-time kilonova light.

They begin by adopting the most popular model for coalescing neutron stars, which posits that a small amount (typically a few hundredths of a solar mass) of radioactive, neutron-rich nuclei gets ejected from the system at high velocities. These radioactive nuclei subsequently decay, synthesizing heavy elements and powering the electromagnetic transient (the kilonova). They further tweak this basic model by segregating the ejected material into two distinct components. First, an equatorial region of extremely high line opacity (photons are absorbed and reemitted many, many times) produced by electronic transitions in atoms of heavy elements — specifically, lanthanides, which have atomic numbers ranging from 57 to 71. Second, a much lower-opacity polar region of ejecta that consists of “lanthanide-free” atoms. Such a
two-component system is currently very popular, and thought by many (but, not all) to be demanded by both theory\textsuperscript{6} and observation\textsuperscript{7}. Demonstrating unambiguously that the proposed lanthanide-free region exists would be a major advance.

\textbf{Fig. 1 | The polarization of light expected from a kilonova 1.5 days after the neutron star merger.} Significant electron-scattering opacity — producing highly polarized photons — exists in the lanthanide-free region of material ejected in the polar directions, whereas line-scattering opacity — producing unpolarized photons — dominates in the lanthanide-rich region of material ejected in the equatorial plane. \textbf{a}, When viewed from above, an unresolved source yields zero net polarization ($P_{\text{net}} = 0\%$) due to complete cancellation of the directional components. \textbf{b}, When viewed from the equator, however, the partial obscuration of the electron-scattering region results in incomplete cancellation, yielding a non-zero net polarization ($P_{\text{net}} > 0\%$).

Of particular significance to polarization studies is the fact that any “bound-bound” line scattering experienced by a photon completely destroys its polarization. Thus, we may anticipate that the resulting net polarization for a kilonova will depend strongly on the relative importance and locations of electron scattering (highly polarizing) compared with line scattering (depolarizing) in the atmosphere.

Armed with this physical model, Bulla et al. produce the polarization characteristics of the emerging optical kilonova light as functions of both time and viewing angle. The headline? We must catch kilonovae early! Beyond two days post-merger, all polarization vanishes, rendering polarimetry impotent as a geometric probe. This happens due to the overwhelming dominance of line opacity compared with electron-scattering in all regions of the ejected material (both equatorial and polar) once it has expanded and cooled sufficiently. In this regard, the null polarization observed for AT 2017gfo during the last four
epochs (all > 2 days post-merger) is both expected and unremarkable.

But at earlier times, the situation is profoundly different. Large polarizations are, indeed, possible, and are highly dependent on viewing angle: Equatorial views at 1.5 days produce expected polarization levels approaching 1% while polar views yield nothing. The reason is geometry. Even at these early times, polarization from electron-scattering can only be generated by the lanthanide-free polar regions; in the equatorial regions, line-scattering by the lanthanide elements is found to always completely depolarize the light. Thus, we have a special — and, fleeting — situation in which an obscuring equatorial “belt” partially blocks an electron-scattering atmosphere. This generates a net polarization for equatorial views (Fig. 1b) but, since there is no obscuration, zero polarization for polar views (Fig. 1a). Intermediate orientations fall in between. (Note that the shape of the electron-scattering photosphere is shown to have surprisingly little impact on the resulting polarization, and so it is assumed spherical.) The upshot of this modeling is that the null polarization measurement made 1.46 days post-merger — formally, the polarization is measured to be less than 0.18% at 95% confidence — constrains the viewing orientation of AT 2017gfo to be within $\sim 65$ degrees of being pole-on.

These new models beg for more data from future events, since they are at once eminently falsifiable, potentially restrictive, and alluringly predictive. Falsifiable since any detection of intrinsic polarization beyond a few days post-merger would demand a major rethink of a popular model’s assumptions. Potentially restrictive since unanimously null polarization measured for many objects observed at sufficiently early times (and, presumably, viewing orientations) would severely limit the possible vertical extent of the proposed lanthanide-rich region in kilonovae.

Of course, a definitive detection of early-time polarization that rapidly falls to zero would be hailed as soaring validation of the model’s basic components. But would it, as Bulla et al. assert, “unambiguously reveal the presence of a lanthanide-free ejecta component”? To some, perhaps. But polarimetry is a tricky business.

References

1. Goldstein, A. et al. *Astrophys. J. Lett.* **848**, L14 (2017). 1710.05446.

2. Bulla, M. et al. *Nat. Astron.* **3**, 99–106 (2019). 1809.04078.
3. Covino, S. et al. *Nat. Astron.* **1**, 791–794 (2017). 1710.05849.

4. Hjorth, J. et al. *Astrophys. J. Lett.* **848**, L31 (2017). 1710.05856.

5. Li, L.-X. & Paczyński, B. *Astrophys. J. Lett.* **507**, L59–L62 (1998). astro-ph/9807272.

6. Kasen, D., Fernández, R. & Metzger, B. D. *Mon. Not. R. Astron. Soc.* **450**, 1777–1786 (2015). 1411.3726.

7. Pian, E. et al. *Nature* **551**, 67–70 (2017). 1710.05858.