Expanding Horizons

Transforming Astronomy in the 2040s

Shedding visible light on the origin of Fast Radio Bursts

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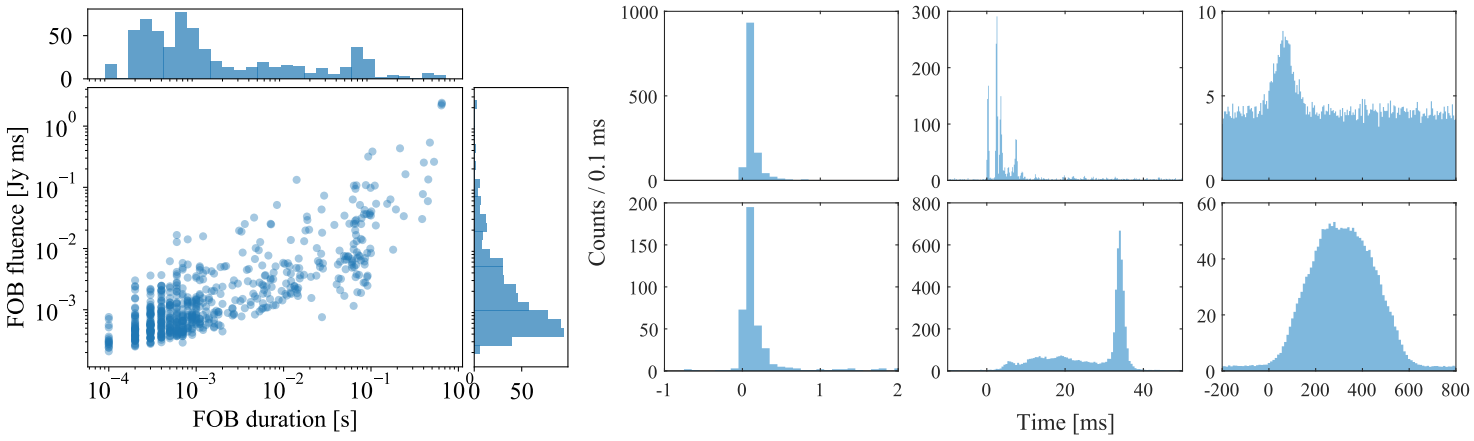
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1 Introduction and Background

After more than 15 years of detections, we still lack a comprehensive explanation for fast radio bursts (FRBs) and their observed properties. They are flashes of millisecond duration with dispersion measures (DMs) that characterize them as extragalactic, the highest brightness temperatures of any astrophysical transient ($\sim 10^{36}$ K), and fluences high enough that, when accurate distances are available, their equivalent isotropic energies are estimated to reach up to $\sim 10^{41}$ erg (e.g. Petroff et al., 2022). They are consistent with being isotropically distributed across the sky with all-sky equivalent daily rates numbering in the hundreds with current surveys (CHIME/FRB Collaboration et al., 2021), therefore also constituting a promising independent probe for near-future cosmological studies (e.g. Macquart et al., 2020, James et al., 2022, Gao et al., 2025). Most FRBs are observed as single events, but a few dozen sources have now shown repeat bursts even years later; two of these sources display periodic activity windows (CHIME/FRB Collaboration et al., 2020a, Rajwade et al., 2020). A large number of possible explanations have been proposed, including a family of models that invoke FRB production around a cosmological population of magnetars, especially young ones, either close within the magnetosphere or in outer shocks (see e.g. Zhang, 2023). At present, we cannot exclude the possibility that multiple mechanisms contribute to the observed bursts. The detection of an FRB-like event from the galactic magnetar SGR 1935+2154, coinciding with X-ray bursting activity, provided the first association of multiwavelength emission to an FRB, and significantly strengthened the magnetar scenario (CHIME/FRB Collaboration et al., 2020b, Mereghetti et al., 2020, Bochenek et al., 2020). Since then, it remains the only such event observed within our Galaxy and the only one with multiband detections.

As different models can entail very different emission behaviours at higher-energy wavelengths, some observational campaigns are beginning to focus on multiband observations to constrain the production mechanisms and sites of FRBs (see Zhang, 2024, and references therein). The optical band is now being probed both for prompt (i.e. burst-like and close in time to possible FRBs) and persistent emission, at various timescales, studying both repeating FRBs (rFRBs) and SGR 1935+2154 (Hardy et al., 2017, Pilia et al., 2020, Lin et al., 2020, Kilpatrick et al., 2021, Trudu et al., 2023, Kilpatrick et al., 2024, Lin et al., 2020, Zampieri et al., 2022). Current prompt optical limits simultaneous with either radio or X-ray bursts have been set at $\sim$16.4 mag (10^{-3} Jy ms) and $\sim$15.7 mag (17.9 Jy ms) for rFRBs and SGR 1935+2154 respectively (Trudu et al., 2023, Zampieri et al., 2022, with lightcurves binned at 1 ms, magnitudes not corrected for extinction), both employing fast photometers capable of counting single photons. Such results place the first upper limits on the optical-to-radio efficiency in FRB emission, which, however, remain compatible with most theoretical models (Yang et al., 2019, Chen et al., 2020, Lin et al., 2020, Kilpatrick et al., 2024).

Besides the need for an observational setup capable of significantly lowering these limits, an additional difficulty is being revealed by ongoing optical campaigns at high time resolution (e.g. those carried out with the ultra-fast optical photometers SiFAP2 at the Telescopio Nazionale Galileo and Aqueye/Iqueye at the Asiago telescope). A large population of transient optical events on a broad range of timescales and fluences is emerging (see Fig. 1). The observed rates, equivalent to more than 10^{10} events per day over the whole sky, clearly indicate that they cannot all have an astrophysical origin. Ongoing statistical analyses of the observed event population (e.g. Campa et al., in prep.) suggest that they arise from a variety of phenomena (including space debris and satellite transits, meteor showers, atmospheric events, and - albeit with marginal significance so far - astrophysical events). Regardless of their origins, it is evident that any future search for an optical event associated with an FRB will have to contend with an extensive



(a) (b)

Figure 1: (a) - Fluence and duration distribution of the fast optical transients observed in SiFAP2 archival observations. (b) - Selection of lightcurves with different shapes and timescales from the same dataset. The equivalent V-band magnitudes of this sample range from about 15 to about 9.

background of non-astrophysical events.

2 Open Science Questions in the 2040s

To date, no simultaneous detection of radio and optical bursts has been reported, either from rFRBs or Galactic magnetars. However, the field is rapidly evolving thanks to both multiwavelength campaigns and large-scale analyses of archival data from promising fast instruments. The latter must be capable of achieving good statistical significance in photon counts even while integrating over intervals short enough to detect the fast variability expected from these systems. It appears highly likely that, given the growing interest and the high event rates in the two bands, by the 2040s at least a few simultaneous events will have been detected, both for brighter extragalactic sources and galactic systems. In that scenario, dedicated extensive searches within the optical band will be able to address some crucial points driving FRB science, all tightly related:

- Provide a large enough statistical sample to study the properties of FRB optical counterparts, in terms of variability, incidence of multiwavelength associations, and temporal shape of the bursts;
- Accurately localize the sources in ∼real-time to provide fast follow-up observations, constraints on energetics, and information on the environments in which they are produced;
- Map the density of the intergalactic medium and provide independent constraints on the values of cosmological parameters;
- Probe the currently unconstrained fainter end of their energy distribution;
- Discern whether only one mechanism is responsible for the observed population of bursts, or if multiple sources are producing events that only currently appear to be the same;
- Provide independent confirmation of the astrophysical origin of fast optical transients;
- For the bursts that will be proven to be related to magnetars:

– Explore the regions in which both the radio emission and the high-energy counterparts are produced, characterizing the extreme environments of their magnetospheres;

– Study the possible evolutionary history of magnetars and their observed behaviour;

– Search for both short- and long-term periodicities, thus exploring the possible evolution of the magnetic alignment of the star's field and its rotation.

3 Technology and Data Handling Requirements

Next-generation facilities aiming to tightly constrain FRB models will need far higher sensitivities. An improvement to the limiting magnitudes down to $\sim 22 - 23$ mag would make it possible to start probing the fluences expected for optical counterparts in the case of the fainter curvature radiation and maser emission models, and, in case of non-detection, rule out a significant fraction of other emission mechanisms (see e.g. Yang et al., 2019, Kilpatrick et al., 2024). That would entail a telescope, or array of telescopes, with an effective diameter of $\sim 20 - 25$ m. Since FRBs also exhibit a wide variety in their polarization light-curves, simultaneous polarimetry would enable better characterization of the source's geometry and help discern whether the optical emission is co-located with the radio source. Time resolution down to at least µs scales will be paramount to probe the fast variability already observed in FRBs. Searches for any fast optical transient, not just FRB counterparts, will also require coverage by at least two, if possible identical, instruments simultaneously. Given this constraint, a single facility comprising multiple telescopes would be advantageous compared to coordinating simultaneous observations across multiple facilities.

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