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Modelling of early-stage kilonova ejecta opacity reproducible in laboratory plasmas

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Summary. — In the framework of the multi-messenger astronomy, for a complete understanding of the heavy elements nucleosynthesis, investigation of the kilonova (KN) emission is crucial. The KN is a thermal transient signal following gravitational-wave events from the coalescence of compact objects. Modelling the KN light-curve is challenging: besides the difficulties in modelling the r-process synthesised elements, it requires several inputs, among which plasma ejecta opacity is still extremely uncertain. In this context, the PANDORA project aims at measuring, for the first time, opacities of a plasma resembling the plasma ejecta through which KN diffuses. In view of that, we present numerical estimates of argon plasma opacity perturbed by an external radiation flux under non local thermodynamic equilibrium. Simulations performed serve as demonstrator for further metallic elements, and their results underline that both thermodynamic parameters and radiation could impact on the opacity of the plasma.

1. – Introduction

In the Universe, the nucleosynthesis beyond iron group elements occurs thanks to neutron capture processes. It deals with neutron-capture reactions, in conjunction with β-decays, in which a free neutron is captured from the surrounding medium before its decay followed by the emission of a photon. Two are the main neutron capture processes: the slow (s-) [1] and the rapid (r-) processes [2]. The observation of the electromagnetic

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(*) E-mail: `matteo.bezmalinovich@uniroma1.it` counterpart of the GW170817 event provided evidence that the coalescence of binary neutron stars (BNS) systems is a favourable stellar site hosting the r-process (neutron densities $n_\mathrm{n} > 10^{22}\,\mathrm{cm}^{-3}$ and temperatures $T > 10^9\,\mathrm{K}$). Following the BNS, an accretion disk is formed from which neutron-rich material is ejected. The high flux of neutrons and the thermodynamic conditions favour neutron capture processes which lead to the formation of heavy isotopes. Due to their instability, these isotopes radioactively decay with the consequent emission of photons that thermalise with the medium and, in the end, generate electromagnetic counterparts such as the kilonova (KN). The KN is a quasi-thermal transient which emits over the whole solid angle. This transient is powered by the radioactive decay of heavy neutron-rich isotopes produced from the r-process nucleosynthesis. The KN light-curve evolves on timescales of days to weeks [3]: for a GW170817-like kilonova, in the early-stage (∼0.5–1 days after the merger) the KN shines at optical wavelengths, moving to infrared after one week. The KN luminosity mainly depends on the thermal energy produced during the element nucleosynthesis and on the plasma ejecta opacity. Modelling the ejecta opacity points to the necessity of overcoming uncertainties in opacity calculations arising from often oversimplified atomic structure models [4-6], leading to inconsistencies between theoretical predictions and observational data for KN. In this context, novel progresses on such aspect can be achieved by means of numerical models and in-laboratory experiments. On the one side, the design and the improvement of laboratory facilities will benefit from numerical prediction for opacity, in order to measure it experimentally. On the other side, the model will address the measurements in a more accurate way and help the community in interpreting the experimental results.

2. – Kilonova plasma ejecta opacity

In literature, early theoretical models proved in detail that r-process nuclei abundances as well as radiation transport, solving the radiative transfer eq. (RTE), must be taken into account to reproduce accurately the shape of KN light-curve spectra [3]. Both the nuclear heating rate and the opacity κ affect the KN emission and the diffusion time peak ($t_\mathrm{peak} \propto 1.6\,\mathrm{days}\,(\kappa/(1\,\mathrm{cm}^2\mathrm{g}^{-1}))^{\frac{1}{2}}$ [7]). The opacity plays an intricate role in the atomic physics between the spreading photons and the r-process nuclei of the expanding ejecta. On the one hand, many RTE models assume κ as an input parameter since it regulates the motion of the photons into the plasma ejecta. On the other hand, to investigate the plasma ejecta opacity is necessary to recreate an environment similar to the astrophysical scenario in which it will be possible to determine and measure accurately plasma thermodynamic parameters. The ideal scenario should consider a plasma whose properties resemble the ones of the KN ejecta including a full-spectrum composition of r-process nuclei, but reproducing all of this in laboratory is extremely difficult. In this context, the on-construction PANDORA (Plasma for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry [8]) facility aims at experimentally exploring the early-stage KN spectral features and the opacity arising from few light r-process nuclei in low ionised confined plasmas under non-Local Thermodynamic Equilibrium (nLTE) conditions. As resulting from a feasibility study and preliminary in-plasma measurements [9, 10], it will be possible to reproduce KN plasma environment (densities of $n_\mathrm{e} \sim 10^{10}$–$10^{13}\,\mathrm{cm}^{-3}$ and temperature of few eV) which is expected to be related to the early-stage KN visible peak, characterised by a dominant light r-process nuclei abundance. In this framework, numerical test-bench estimations of nLTE plasma thermodynamic parameters and argon plasma opacity have been performed and discussed in sect. **3**.

3. – Opacity results from numerical simulations

Differently from the theoretical scenario, in our simulations, we focused only on a single species: the argon. This choice was induced predominantly by the easy reproducibility of argon plasma in laboratory, in view of future experimental campaigns for direct opacity measurements to be compared with the outcomes of the numerical simulations. First of all, we developed a numerical code to extrapolate electron density n_e (cm^{-3}) and temperature T_e (eV) of a simulated non-homogeneous Electron Cyclotron Resonance (ECR) plasma under nLTE conditions along a 1D line. The plasma data rely on particle-in-cell codes capable to catch the plasma dynamics in compact magnetic trap as PANDORA [11]. In particular, plasma parameters here presented refer to a compact magnetic trap in Debrecen, ATOMKI, where previous experimental campaigns were performed and parameters measured. We therefore studied the plasma opacity as a function of n_e and T_e. In the same study, the impact of an external radiation perturbing the medium was considered. For such study we focused on the absorption lines of argon. A black-body (BB) radiation at temperature $T_\mathrm{r} = 8000\,\mathrm{K}$ was assumed for studying the plasma perturbation. By means of the kinetic population code FLYCHK [12], we derived the opacity spectrum $\kappa(\lambda)$ ($\mathrm{cm}^2\mathrm{g}^{-1}$) for all transitions by computing the atomic level population, producing the synthetic spectra of the absorption coefficient $\alpha(\lambda)$ (cm^{-1}), where $\alpha(\lambda) = \kappa(\lambda)\rho_\mathrm{Ar}$ (ρ_Ar is the argon density in $\mathrm{cm}^{-3}\mathrm{g}$). The opacity $\kappa(\lambda)$ for a transition is proportional to the upper $\mathcal{N}_\mathrm{u}$ (lower $\mathcal{N}_\mathrm{l}$) level population density as $\kappa_\lambda \propto \mathcal{N}_\mathrm{l}\,(1-\mathcal{N}_\mathrm{u}/\mathcal{N}_\mathrm{l})$. The opacity spectra were reconstructed in the visible range [380,700] nm, including the impact of the BB radiation at various intensity (up to $\sim 10^{32}$ photons $\mathrm{s}^{-1}\mathrm{m}^{-2}$). Figure 1 shows numerical estimates of argon plasma opacity as a function of the plasma density (fig. 1(a), (b)) and the temperature (fig. 1(c)).

Since the opacity can be related to the coupling between radiation and matter (*i.e.*, photons and electrons) from fig. 1, it can be evinced that $\kappa(\lambda)$ values increase while increasing the density: the higher the number of electrons into the medium is, the higher $\mathcal{N}_\mathrm{l}$ will be with the consequent increase of the opacity value ($\sim 10^{-4}$). Otherwise, decreasing n_e leads to smaller $\mathcal{N}_\mathrm{l}$ values with the consequent drop of κ values. Moreover, comparing fig. 1(a) with (b), it can be seen that the introduction of the radiation increases the plasma transparency ($\kappa(\lambda) \sim 10^{-6}\,\mathrm{cm}^2\mathrm{g}^{-1}$). This results in a consequent equal distribution between $\mathcal{N}_\mathrm{l}$ and $\mathcal{N}_\mathrm{u}$ levels, reducing the opacity. Figure 1(c) shows the behaviour of the opacity in correspondence to the plasma temperature regions. On the one side, among the regions with $T_\mathrm{e} \sim 140, 138\,\mathrm{eV}$, the high temperature provides energy to

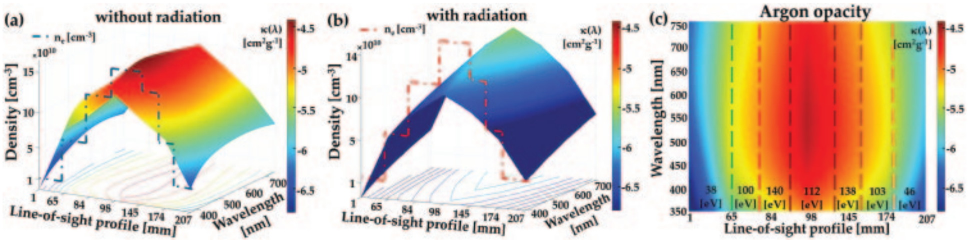

Fig. 1. – Argon opacity behaviour along the plasma line-of-sight as a function of the wavelength and the thermodynamic parameters n_e ((a), (b)) and T_e (c). The opacity has been studied in both scenarios: unperturbed ((a), (c)) and perturbed (b) by BB radiation (photon flux $\sim 10^{32}\,\mathrm{s}^{-1}\mathrm{m}^{-2}$).

the electron causing a downshift of the opacity, while, on the other side, the intermediate region at $T_e \sim 112\,\mathrm{eV}$ still results in a higher opacity value due to the high n_e. Similar numerical simulations have been performed to investigate different isotopes of interest for the early-stage KN environment (Se, Sr, Zr and Nb) [10]. The increase of the element atomic number and shell complexity (*i.e.*, pushing from argon to elements of astrophysical plasma ejecta) implies more electrons in $\mathcal{N}_1$, with complex valence electron shells, resulting in different opacities.

4. – Conclusions

In the context of multi-messenger astronomy and of KNe, in this paper we presented numerical estimations of plasma opacities in the visible range. The simulations have been carried out with a nLTE argon plasma as benchmark for astrophysical elements of interest for the early-stage KN scenario under the presence of an external radiation flux. The results highlight the strongly dependence of the plasma opacity behaviour as a function of the plasma thermodynamic parameters and the radiation. Considerable efforts are still needed to converge to an improved and reliable set of atomic structure data that we reckon to calculate by focusing on numerical codes which could better address the opacity estimation. These numerical investigations will be compared later to the calculated opacity in the literature and to planned experimental data and tested in the framework of RTE codes to reproduce KN light-curves accurately. Among the RTE codes available [13-15], POSSIS (POlarization Spectral Synthesis In Supernovae [16]) is a time-dependent 3D Monte Carlo radiative transfer code developed for modelling radiation transport in supernovae and KN. Since it adopts as input pre-computed tables of atomic opacities, the code represents the perfect tool to test newly experimental opacity datasets.

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