The Radiative Transfer and Atomic Physics of Kilonovae

Sep 4, 2023, 9:20 AM → Sep 7, 2023, 3:00 PM Europe/Stockholm
Wenner-Gren Center

Anders Jerkstrand (Stockholm University)

Description

Participants A Albert Sneppen A Anders Jerkstrand A Andreas Flörs B Ben Shenhar L Luke Shingles N Nanae Domoto N Niamh Ferguson N Nicholas Vieira N Nigel Badnell N Nikhil Sarin O Or Guttman P Paul Barklem +36

Monday, September 4

9:30 AM → 10:45 AM **Monday morning: Block 1. Chair: Anders Jerkstrand**

9:30 AM **Welcome** 15m
Speaker: Anders Jerkstrand (Stockholm University)

9:45 AM **TBD** 55m
Speaker: Camilla Juul Hansen (Frankfurt University)

10:45 AM → 11:05 AM **Break** 20m

11:05 AM → 12:40 PM **Monday morning: Block 2. Chair: Stephan Rosswog.**

11:05 AM **TBD** 55m
Speaker: Gabriel Martinez-Pinedo

12:00 PM **General Relativistic Magnetohydrodynamic Simulations of Proto-Neutron Stars** 20m

I present general relativistic magnetohydrodynamic simulations of one potential r-process site associated with core collapse supernovae: the neutrino-driven wind. These outflows are launched from a hot proto-neutron star (PNS) remnant by neutrino-heating above their surfaces, within seconds after the collapse of a massive star. Previous work has shown that spherically symmetric winds from non-rotating PNSs fail to achieve the requisite conditions for a robust r-process. I explore for the first time the combined effects of rapid rotation and strong gravity of the PNS on the wind properties. I then explore the impact of a dynamically strong ordered magnetic field on the properties of non-rotating PNS winds. The wind in both cases is simulated in a controlled environment rather than as a part of a self-consistent global CCSNe simulation, to assess the viability of r-process nucleosynthesis as a function of PNS properties (neutrino energies/luminosities, rotation rate, magnetization). In future works I will combine the effects of rapid rotation and high magnetization in order to explain (according to the 'magnetar origin' model from Metzger et al. 2018) the observed fast, high-mass ejecta inferred from the 'blue KN' associated with GW170817.

Speaker: Dhruv Desai

12:20 PM **Nucleosynthesis and Kilonova in neutron star mergers: effects of nuclear matter properties** 20m

Matter expelled from binary neutron star (BNS) mergers can harbor r-process nucleosynthesis and power a Kilonova (KN), which represents a major EM counterpart to gravitational wave (GW) signals.
Both the elemental yields and the subsequent KN transient are intimately related to the astrophysical conditions of the merger ejecta, which in turn indirectly depend on the EOS describing the nuclear matter inside the NS.
In particular, the dynamical evolution of the merger is influenced by specific nuclear matter properties that characterize the EOS at nuclear saturation density.
In this study we consider the outcome of a set of BNS merger simulations employing different finite-temperature nuclear EOSs, obtained from Skyrme-type interaction models.
We thus follow the merger ejecta evolution using a nuclear reaction network coupled with a semi-analytic photon transport scheme.
The final elemental abundances and the associated early KN are found to be systematically influenced by the nuclear matter properties used to parametrize the EOS, specifically the incompressibility and the nucleon effective mass at saturation density.
The latter modify the pressure inside the NS and its slope as a function of density, with a non-trivial impact on the amount of each ejecta component.

Speaker: Giacomo Ricigliano (Technical University of Darmstadt)

12:40 PM → 2:10 PM

Lunch break 1h 30m

2:10 PM → 3:45 PM **Monday afternoon: Block 1. Chair: Masaomi Tanaka.**

2:10 PM **TBD** 55m

Speaker: Dan Kasen (UC Berkeley)

3:05 PM **Multi-dimensional kilonova radiative transfer from merger simulations** 20m

The detection of GW170817 and the accompanying electromagnetic counterpart, AT2017gfo, have provided an important set of observational constraints for the high density Equation of State and r-process nucleosynthesis. To interpret the observations of AT2017gfo, detailed theoretical models are required. The majority of binary neutron star ejecta models considered when simulating kilonovae have been in 1D, or even idealised toy models, which have neglected the complexities related to hydrodynamics modelling. Few kilonova simulations have carried out full 3D simulations of the merger and subsequent kilonova. We use the 3D Monte Carlo radiative transfer code ARTIS to carry out simulations based on the dynamical ejecta from 3D smoothed-particle hydrodynamics neutron star merger simulations, including a sophisticated neutrino treatment. We present line-of-sight dependent synthetic observables, and discuss the angle dependence, as well as compare to the observations of AT2017gfo.

Speaker: Christine Collins (GSI Helmholtz Centre for Heavy Ion Research)

3:25 PM **Comparing Radiative Transfer Methods for Kilonovae** 20m

The electromagnetic signals from the kilonova AT2017gfo present an opportunity to study an astrophysical site of the r-process which is considered to produce about half of the elements heavier than iron. The decline of the bolometric light curve is broadly consistent with being powered by the decays of unstable nuclei expected from r-process nucleosynthesis. The light curve is sensitive to the amount and composition of ejected matter as well as the actual ejection process itself. Several attempts have been made to reproduce the light curve, often with a number of simplifying assumptions, but reproducing the light curve self consistently is a challenging task. We compare two different methods for simulating kilonova light curves using two multi-dimensional radiative transfer codes: Monte Carlo radiative transfer (ARTIS code) and solution to the moment equations of the radiation pressure tensor (ALCAR code). Our aim is to benchmark the ALCAR code with the well-established though computationally more expensive ARTIS code. Because of ALCAR's computational advantages, this will allow for an efficient exploration of the large parameter space before investigating more specific regions in greater detail with ARTIS.

Speaker: Gerrit Leck (GSI Helmholtzzentrum für Schwerionenforschung GmbH)

3:45 PM → 4:15 PM **Break** 30m

4:15 PM → 5:10 PM **Monday afternoon: Block 2. Chair: Mattia Bulla.**

4:15 PM **Trials and Tribulations with Kilonova Transport** 55m

The concurrent gravitational- and electromagnetic wave observations of GW170817 both proved the importance of neutron star mergers in the production of r-process elements and demonstrated the difficulties in accurately estimating the mass from EM emission. Although a growing number of potential "kilonovae" have been observed associated with short (and long) gamma-ray bursts, these events prove even more difficult to analyze with existing radiative transport models. These difficulties arise from a combination of issues including uncertain initial conditions, accurate calculations of energy deposition, and uncertainties in the opacity determinations and implementations. Here we review these uncertainties, covering the effects placed by uncertain initial conditions, energy deposition and transport schemes with a focus on recent potential kilonova events.

Speaker: Chris Fryer (Los Alamos National Laboratory)

Tuesday, September 5

9:30 AM → 10:50 AM **Tuesday morning: Block 1. Chair: Stephen Smartt.**

9:30 AM **Perspectives for kilonovae multimessenger detection** 20m

The detection of the gravitational wave (GW) signal GW170817 and the electromagnetic (EM) signal AT2017gfo confirmed the association between binary neutron star (BNS) mergers and kilonovae (KNe) and showed the potential of joint detection to unveil the nature of neutron stars and the nucleosynthesis of heavy elements in the Universe. The next-generation GW interferometers, such as the Einstein Telescope, are unprecedented resources to enhance the chances of detecting EM counterparts significantly enlarging the horizon of detectable BNS mergers, and dramatically improving the source parameter estimation. In this context, providing reliable predictions about GWs and KNe joint detections is pivotal to developing detection strategies and evaluating the multi-messenger science potential. Starting from BNS merger populations based on population synthesis codes, we compute the number of detected mergers and estimate the source parameters within a Fisher-matrix approach for different configurations of ET. We evaluate the KNe emission both assuming AT2017gfo-like signals or modelling the KN parameters via numerical-relativity-informed fits for two different EOSs. We evaluate the perspectives for ET observing in synergy with the Vera Rubin Observatory (VRO) looking at the impact of GWs and KNe joint detections on constraining the EOS and for cosmology studies.

Speaker: Eleonora Loffredo (GSSI / INFN / INAF)

9:50 AM **Confronting kilonovae models with observations: What do we need?** 20m

Since the extraordinary observations of AT2017gfo, we have seen many complementary advancements in our capability to observe kilonovae and model them. However, our sample of confident kilonovae candidates remains small, with many candidates since AT2017gfo contaminated by the afterglow from a gamma-ray burst. In this talk, I will highlight the issues we need to resolve to decouple kilonovae from afterglows and confront our growing list of candidates and showcase tools necessary to extract physics from future kilonovae observations.

Speaker: Nikhil Sarin (Stockholm University)

10:10 AM

Illuminating neutron star mergers with the 3D Monte Carlo radiative transfer code POSSIS 20m

The detection of an electromagnetic counterpart to the gravitational-wave source GW 170817 marked year zero of the multi-messenger gravitational-wave era. This event was generated by the coalescence of two neutron stars and gave rise to an electromagnetic transient, dubbed a “kilonova”, powered by the radioactive decay of heavy (r-process) nuclei synthesised during the merger. In this talk, I will show how radiative transfer simulations can illuminate neutron star mergers and provide a connection between numerical models of neutron star mergers and observational data. I will present the 3D Monte Carlo radiative transfer code POSSIS and show how viewing-angle dependent predictions - such as spectra, light curves and polarization - of kilonovae can be used to interpret data, place constraints on models and guide future follow-up campaigns of gravitational-wave events.

Speaker: Mattia Bulla (University of Ferrara)

10:30 AM

The spherical nature of AT2017gfo 20m

The geometry of kilonovae is a key diagnostic of the physics of merging neutron stars, with current hydrodynamical merger models typically showing aspherical ejecta. Previously, we identified SrII in the spectrum of the only well-studied kilonova AT2017gfo, associated with the gravitational wave event GW170817. In this talk, I will show that the strong Sr II P Cygni absorption-emission spectral feature and the luminosity of the kilonova can be used to accurately determine the shape of the kilonova at early epochs. We find highly spherical geometry. Line shape analysis combined with the measured inclination angle of the source also independently shows the same sphericity. The near-spherical geometry suggests early spectra of kilonovae may provide excellent precision cosmic distance measurements using the Expanding Photosphere Method given the extremely small dilution factor corrections expected in kilonovae. Lastly, I will show the potential constraints attainable given detections in LIGO runs O4/O5.

Speaker: Darach Watson (Niels Bohr Institute, University of Copenhagen)

10:50 AM → 11:10 AM **Break** 20m

11:10 AM → 12:45 PM **Tuesday morning: Block 2. Chair: Chris Fryer.**

11:10 AM

TBD 55m

TBD

Speaker: Masaomi Tanaka (Tohoku U.)

12:05 PM

The thermalization of gamma-rays in radioactive expanding ejecta: A simple model and its application for Kilonovae 20m

The observed luminosity of astronomical transients, such as Type Ia supernovae (Ia SNe) or Kilonovae (KNe) that follow neutron star mergers (NSMs), is powered by radioactive decay of unstable nuclei in rapidly expanding ejecta. Understanding the thermalization process of high energy particles produced by radioactive decay is essential for modeling the light curves, and thus for inferring from observations the ejecta properties, including mass, velocity and, in the case of KNe, composition. This, in turn, is crucial for determining the role of NSMs in the formation of heavy elements.
In this work, we study the thermalization of gamma-rays, over a wide range of ejecta compositions and densities. A simple semi-analytical model is presented for the time-dependent fraction of the gamma-ray energy deposited in the ejecta. We verify the model using Monte-Carlo simulations and we show it can be approximated using an effective frequency-independent gamma-ray opacity, which defines a timescale for the onset of inefficient gamma-ray deposition.
For KNe, we derive the effective gamma-ray opacity for a wide range of initial neutron richness, initial entropies and column densities.
We show that the results are insensitive to the (large) uncertainties in the nuclear mass model and in the theoretical values of unmeasured reaction rates.
The method described in this work can be applied to any radioactive ejecta. In particular, it reproduces the effective gamma-ray opacity used in Ia SNe modeling without the need to discard the contribution of the low-energy X-rays in an ad-hoc manner, as was done in the past. Furthermore, we discuss the applicability of the method to fast blue optical transients (FBOTs), short-duration events which may be powered by radioactive heating, and derive the gamma-ray effective opacity for nickel-powered FBOTs.

Speaker: Or Guttman (Weizmann Institute of Science)

12:25 PM

Self-consistent 3D kilonova radiative transfer modeling pipeline: from merger simulations to directional spectra 20m

We present three-dimensional radiative transfer calculations for the ejecta from a neutron star merger that include line-by-line opacities for tens of millions of bound-bound transitions, composition from an r-process nuclear network, and time-dependent thermalization of decay products from individual α and β^- decay reactions. In contrast to expansion opacities and other wavelength-binned treatments, a line-by-line treatment enables us include fluorescence effects and associate spectral features with the emitting and absorbing lines of individual elements. We find variations in the synthetic observables with both the polar and azimuthal viewing angles. The spectra exhibit blended features with strong interactions by Ce III, Sr II, Y II, and Zr II that vary with time and viewing direction. We demonstrate the importance of wavelength-calibration of atomic data

using a model with calibrated Sr, Y, and Zr data, and find major differences in the resulting spectra, including a better agreement with AT2017gfo. The synthetic spectra for near-polar inclination show a feature at around 8000 Angstrom, similar to AT2017gfo. However, they evolve on a more rapid timescale, likely due to the low ejecta mass (0.005 $M_\odot$) as we take into account only the early ejecta. The comparatively featureless spectra for equatorial observers gives a tentative prediction that future observations of edge-on kilonovae will appear substantially different from AT2017gfo. We also show that 1D models obtained by spherically averaging the 3D ejecta lead to dramatically different direction-integrated luminosities and spectra compared to full 3D calculations.

Speaker: Dr Luke Shingles (GSI Helmholtzzentrum für Schwerionenforschung GmbH)

2:10 PM → 3:45 PM **Tuesday afternoon: Block 1. Chair: Jon Grumer.**

2:10 PM **Atomic structure calculation using the General Relativistic Atomic Structure Package (GRASP)** 55m

There are several computer packages such as HULLAC, FAC, AMBIT, GRASP, COWAN CODE for atomic structure calculations, each having their strengths and weaknesses [1-5]. Here we give an account for GRASP: theory, methodology, and issues of program handling [6,7]. Through a number examples, we discuss the applicability of GRASP for atomic systems of different complexity of relevance for astrophysics. Of special importance is the issue of uncertainty of the calculated energy levels and of the corresponding transition rates. At the end we discuss some future prospects of atomic structure calculations.
References:
[1] A Bar-Shalom, J Oreg, and M Klapisch, J. Quant. Spectros. Rad. Transf. 65, 43 (2000).
[2] M.F. Gu, Canadian Journal of Physics, vol. 86, issue 5, pp. 675-689 (2008).
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[5] R.D. Cowan, The Theory of Atomic Structure and Spectra; University of California Press: Berkeley, CA, USA, (1981).
[6] P. Jönsson et al. Atoms, vol. 11(1), 7 (2023).
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Speaker: Per Jönsson (Malmö Universitet)

3:05 PM **r-process opacities and their effect on kilonova abundance inference** 20m

In 2017, the electromagnetic counterpart AT2017gfo to the binary neutron star merger GW170817 was observed by all major telescopes on Earth. While it was immediately clear that the transient following the merger event, is powered by the radioactive decay of r-process nuclei, only few tentative identifications of light r-process elements have been made so far. One of the major limitations for the identification of heavy nuclei based on light curves or spectral features is incomplete or missing atomic data which greatly affects the results of radiative transfer models.

In this talk, I will present converged large-scale atomic structure calculations of r-process elements, including actinides. The atomic data from such calculations will give insight into the opacities required for radiative transfer modelling. I will show a comparison of bound-bound opacities as a function of included electron configurations, for both ab-initio and experimentally calibrated atomic structure calculations. Using our calibrated as well as published atomic data, I will quantify how sensitive abundance inferences from radiative transfer codes are to the selected atomic data.

Speaker: Andreas Flörs (GSI Darmstadt)

3:25 PM **Optimization of atomic data for improved kilonova modelling** 20m

With the recent detection of multiple neutron-star merger events, the need for a more comprehensive understanding of nuclear and atomic properties, as well as advanced astrophysical simulations, has become increasingly important to accurately predict r-process nucleosynthesis yields and electromagnetic signals when presented with observational data. The lack of atomic data has led to a number of computations of weakly ionised r-process opacities, primarily focusing on lanthanides, being published in recent years. However, if the merging process results in the ejection of material with an electron fraction (Ye) of 0.15 or less, nucleosynthesis should progress to actinides. These elements are expected to have photon opacities comparable to, if not greater than, lanthanides [1,2].
Despite our current understanding, large discrepancies can still be found in the opacities related to the uncertainty of atomic data produced using different methodologies. Having accurate atomic data is crucial for the interpretation of observed spectra. [3] To address this issue, we developed an optimisation technique that produces atomic data (energy levels and oscillator strengths) consistent with experimental data. We make use of the Flexible Atomic Code software package [4] that relies on a single mean potential computed for a single fractional fictitious configuration (FMC), allowing for great computational efficiency. Our method exploits a Sequential Model-Based Optimization (SMBO) procedure to find the best FMC that reproduces available experimental and/or ab-initio data. This allows us to improve the accuracy of final calculations while balancing efficiency and accuracy within our calculations.
In this talk, we will present results from large-scale calculations of data for relevant r-process elements computed using this optimization procedure, with great focus on lanthanide and actinides. Furthermore, we investigated how this optimization technique affects our calculations while comparing with results from other atomic structure codes in order to quantify the uncertainty in atomic data produced using different methodologies. Our goal is to provide a more reliable, while still complete set of atomic data for relevant lanthanides and actinides in the expanding ejecta.

References
[1] R. F. Silva, J. M. Sampaio, P. Amaro, A. Flörs, G. Martínez-Pinedo, and J. P. Marques, “Structure Calculations in Nd III and U III Relevant for Kilonovae Modelling,” Atoms, vol. 10, no. 1, p. 18, Mar. 2022, doi: 10.3390/atoms10010018.
[2] A. Flörs et al., Opacities of Singly and Doubly Ionised Neodymium and Uranium for Kilonova Emission Modeling. arXiv, 2023. doi: 10.48550/arXiv.2302.01780.
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Speaker: Ricardo Ferreira da Silva (Laboratório de Instrumentação e Física Experimental de Partículas (LIP))

3:45 PM → 4:15 PM **Break** 30m

4:15 PM → 5:30 PM **Tuesday afternoon: Block 2. Chair: Henrik Hartman.**

4:15 PM

EXPERIMENTAL RESEARCH ON R-PROCESS ELEMENTS 55m

The cosmological origin of those elements heavier than iron continues to puzzle scientists across different fields of science. Spectral analysis of the transient radiation AT 2017gfo emitted after the merging of two neutron stars, known as a kilonova, points at these events as a good candidate for the creation of the heavy elements through rapid neutron capture (r-process).

To unlock the invaluable information contained in kilonovae spectra, astronomers require a vast amount of information for these heavy elements. However, the quantity of atomic data available lies very far from the current needs, which makes r-process elements a new priority for laboratories. Furthermore, this need of accurate atomic data is expected to increase even more with the beginning of operations of LIGO 04.

In this talk, I will provide a clear overview of past and present experimental work undertaken by different laboratories around the world to provide accurate experimental atomic data for r-process elements. I will explain the different techniques used in laboratories to measure atomic parameters such as wavelengths, energy levels, lifetimes and transition probabilities, addressing the capabilities and limitations of the different methods.

This talk will provide the foundation and common language on atomic experimental work required to spark conversations between experimentalists and astronomers, groups working on radiative transfer, nucleosynthesis and theoretical calculation of atomic parameters of r-elements. The final aim of this contribution is to foster collaborations as this will help laboratories to define a clear and realistic strategy regarding what data measurements should be prioritised and will be vital to address the study of current and future kilonovae.

Speaker: MARIA TERESA BELMONTE SAINZ-EZQUERRA (UNIVERSIDAD DE VALLADOLID (SPAIN))

5:10 PM

Visible and near infra-red spectroscopy of laser plasmas for astrophysics 20m

Laser produced plasmas (LPPs) are key components for atomic and ionic spectroscopy. They act as sources of neutrals and ions, and of radiation to probe their structure.
Both emission and absorption spectroscopy are facilitated using LPPs. As part of the HEAVYMETAL project, the team at UCD will develop new configurations of LPPs to enhance, and perhaps optimise, populations of desired species.
We will probe these with established and new spectroscopic techniques, ranging from the soft x-ray to the near infra-red, with the explicit intention of contributing to our understanding of Kilonova observations.
In this talk I will introduce the UCD group and outline our plans for research over the next few years. I will present very preliminary, as yet not analysed, experimental spectra of 4th & 6th row elements.

Speaker: Padraig Dunne (University College Dublin)

Wednesday, September 6

9:30 AM → 10:45 AM **Wednesday morning: Block 1. Chair: Chris Fontes.**

9:30 AM

TBD 55m

TBD

Speaker: Nigel Badnell (University of Strathclyde)

10:25 AM

Multi-component Ejecta and Time-Evolving Elemental Abundances in the GW170817 Kilonova 20m

In kilonovae, freshly-synthesized r-process elements imprint absorption features on optical spectra, as observed in AT2017gfo. These spectral features provide insights into the physical conditions of the r-process, but measuring the detailed composition of the ejecta is challenging. Vieira et al. (2023) introduced Spectroscopic r-Process Abundance Retrieval for Kilonovae (SPARK), a tool for performing inference on kilonova spectra to (1) retrieve elemental abundance patterns, and (2) associate individual absorption features with particular species in the early-time, optically-thick spectra. We have applied SPARK to the 1.4 days post-merger spectrum of AT2017gfo and recovered the first element-by-element abundance patterns, characterized by high electron fraction, moderate-high entropy, and considerable velocity, leading to a dearth of lanthanides and heavier elements. We also identified the presence of Strontium, Yttrium, and Zirconium in the ejecta. Now, we extend our analyses to 2.4 and 3.4 days post-merger. In addition, we test the need for multi-component models, where the ejecta is radially stratified in elemental composition. At 3.4 days, a new redder component with lower electron fraction and a significant abundance of lanthanides emerges. We present the time evolution of the element-by-element abundance pattern of AT2017gfo in its optically thick phase. The higher lanthanide fraction at 3.4 days post-merger has important implications for the ability of kilonovae to produce the Universal r-process seen in the Solar system and beyond.

Speaker: Nicholas Vieira (McGill University)

10:45 AM → 11:05 AM **Break** 20m

11:05 AM → 12:40 PM **Wednesday morning: Block 2. Chair: Nanae Domoto.**

11:05 AM

TBD 55m

TBD

Speaker: Chris Fontes (Los Alamos National Laboratory)

12:00 PM **TBD** 20m

TBD

Speaker: Smaranika Banerjee (Stockholm University)

12:20 PM **Non-thermal emission from mildly relativistic ejecta of BNS mergers** 20m

Binary neutron star mergers are expected to produce a relativistic jet and a fast dynamical ejecta, with mildly relativistic velocities extending to $\beta = v/c > 0.6$. We consider the radio to X-ray synchrotron emission produced by collisionless shocks driven by such spherical fast ejecta into the interstellar medium. We provide analytic expressions for this non-thermal emission, which are an accurate description (to 10's of percent) of the evolution of the flux, including at the phase of deceleration to sub-relativistic expansion. This is a significant improvement over earlier results, based on extrapolations of results valid for $\gamma\beta \gg 1$ or $\ll 1$ to $\gamma\beta \approx 1$, which overestimate the flux by an order of magnitude for typical parameter values. Our results will enable a more reliable inference of ejecta parameters from future measurements of the non-thermal emission. We will also present initial results regarding the impact of our improved treatment of the emission from mildly relativistic plasmas on the predicted non-thermal radiation driven by non-spherical (jet/cocoon) components observed off-axis/at late times.

Speaker: Mr Gilad Sadeh (Weizmann Institute)

12:40 PM → 2:10 PM **Lunch break** 1h 30m

2:10 PM → 3:45 PM **Wednesday afternoon: Block 1. Chair: Stuart Sim.**

2:10 PM **Spectral features of kilonova in photospheric phase** 55m

Spectra of kilonovae, radioactively-powered electromagnetic radiation from neutron star mergers, provide us with information of r-process nucleosynthesis. In the photospheric phase, which photons diffuse out from optically thick matter, absorption features in the spectra can be used to identify individual elements. However, the decode of the spectra for the first detected kilonova GW170817/AT2017gfo has not been complete, and the abundances of synthesized elements in this event is not yet clear. In the talk, I will first introduce the difficulty of the identification of elements in the photospheric spectra. Then, I will discuss what information we can extract from absorption features mainly based on our work but as well as other work on the photospheric kilonova spectra.

Speaker: Nanae Domoto (Tohoku University)

3:05 PM **Discovery of a 760 nm P Cygni line in AT2017gfo: Identification of yttrium in the kilonova** 20m

Neutron star mergers are believed to be a major cosmological source of rapid neutron-capture elements, but only limited definite spectral identifiers of these heavy elements have been found. Identifying P Cygni lines are important because they provide significant information not just potentially on the elemental composition of the merger ejecta, but also on the velocity, geometry, and abundance stratification of the explosion. In this talk, we present evidence for a previously unrecognised P Cygni line in the spectra of AT2017gfo that emerges several days after the explosion, located at $\lambda \approx 760$ nm. We show that the feature is well-reproduced by $4d^2$-4d5p transitions of Y^+, which have a weighted mean wavelength of around 760-770 nm, with the most prominent line at 788.19 nm. While the observed line is weaker than the Sr^+ feature, the velocity stratification of the new line provides an independent constraint on the expansion rate of the ejecta, which is consistent with the Sr^+ P Cygni.

Speaker: Albert Sneppen (Niels Bohr Institute, The Cosmic DAWN Center)

3:25 PM **HEAVY ELEMENT OPACITY CALCULATIONS FOR KILONOVA MODELING** 20m

The production of elements heavier than iron in the Universe still remains an unsolved mystery. About half of them are thought to be notably produced by the astrophysical r-process (rapid neutron-capture process) [1], for which one of the most promising production sites are neutron star mergers (NSM) [2]. In August 2017, gravitational waves generated by a NSM event were detected by the LIGO detectors (event GW170817) [3], and the observation of its electromagnetic counterpart, the kilonova AT2017gfo, suggested the presence of heavy elements in the ejecta [4]. The luminosity and spectra of such kilonova emission depend significantly on the ejecta opacity, which is dominated by millions of lines from f-shell elements, i.e. lanthanides and actinides, produced by the r-process [5]. Atomic data and opacities for these elements are thus sorely needed to model and interpret kilonova light curves and spectra.
In this context, an overview of the different calculations that have been carried out in the present works on atomic data and corresponding opacities in open 4d, 5d, 4f and 5f-shell elements for typical ejecta conditions expected both in early-phase and in one day post-merger will be presented. These conditions correspond to the presence of ionization stages ranging from neutral up to nine times ionized. A multiplatform approach has been adopted in order to assess the accuracy of the atomic data where the pseudo-relativistic Hartree-Fock (HFR) method as implemented in the Cowan's codes [6], the multiconfiguration Dirac-Hartree-Fock (MCDHF) method as implemented in the last version of the GRASP2018 package [7] and the configuration interaction with many-body perturbation theory correction method (CI-MBPT) as implemented in the AMBiT code [8] have been used. The data sets produced by the first one have been chosen for the opacity computations. Our atomic data and expansion opacities will be discussed and compared with other studies available in the literature.
References
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Speaker: Patrick Palmeri (Université de Mons - UMONS)

Thursday, September 7

9:30 AM → 10:45 AM **Thursday morning: Block 1. Chair: Jesper Sollerman.**

9:30 AM

The observational properties of kilonovae 55m

I will present a summary of the observational properties of kilonovae. This sample includes AT2017gfo (associated with GW170817) and the more extensive but more sparsely sampled set of kilonovae identified in short and, more recently, in long-duration gamma-ray bursts. The broad photometric properties (peak magnitudes, timescales) are similar in many cases in which kilonovae are seen. However, there are also events in which they are apparently much fainter. I will also highlight the recent mid-IR observations of a kilonova in the long-duration GRB 230307A, providing the first late time and first mid-IR spectroscopy of a kilonova and an important observational focus for future modelling.

Speaker: Andrew Levan (Radboud University)

10:25 AM

Future prospects for UV to near infrared spectroscopic data for kilonovae 20m

A remarkable sequence of spectra were taken every 24hrs for 10 nights of the kilonova AT2017gfo. These covered 0.3-2.2microns at good signal to noise and spectral resolution (with the VLT X-shooter instrument). However AT2017gfo was at the relatively close distance of 40Mpc, and the volumetric rates of BNS mergers now imply this was a once in a decade (roughly) event. Application of radiative transfer models rely on high quality spectral data for comparison. I will review the current and future instruments and facilities for gathering spectroscopic data of kilonovae, and the prospects for data sets of similar quality to AT2017gfo. I will highlight ESO's current and future instruments and space based facilities.

Speaker: Stephen Smartt (University of Oxford)

10:45 AM → 11:05 AM **Break** 20m

11:05 AM → 1:00 PM **Thursday morning: Block 2. Chair: Dan Kasen.**

11:05 AM

TBD 55m

TBD

Speaker: Kenta Hotokezaka (University of Tokyo)

12:00 PM

Kilonova Spectra in the Non-Local Thermodynamic Equilibrium Regime 20m

The electromagnetic transient following a binary neutron star merger is known as a kilonova (KN). KN ejecta evolve rapidly away from Local Thermodynamic Equilibrium (LTE) conditions to a regime where the thermodynamic conditions are defined by Non-Local Thermodynamic Equilibrium (NLTE) processes. In this talk, I will present results from the 1D NLTE modelling of KNe using the spectral synthesis code SUMO. Three homogeneous composition models with characteristic electron fractions Y_e ~ 0.35, 0.25, 0.15 are evolved from 5 to 20 days after merger. I will go over which processes and species are key to KN spectral formation during these epochs, and what this implies for current and future efforts to accurately model and understand emergent kilonova spectra.

Speaker: Quentin Pognan (Stockholm University)

12:20 PM

Analytic Description of Beta Decay e$^{\pm}$ Thermalization in Kilonovae Ejecta 20m

Kilonovae light-curves depend on the efficiency with which beta decay e$^{\pm}$ deposit their energy in the expanding ejecta. We show that the time $t_{\rm e}$, at which the deposited energy fraction drops to $1/e$, depends mainly on ejecta density and velocity, and only weakly on the initial electron fraction Y_e and entropy s_0: $t_{\rm e} = t_0 \times (\rho t^3/(\rho t^3)_0)^{s_{\rm e}}$ days, where $(\rho t^3)_0 = \frac{0.025 M_\odot}{4\pi(0.2c)^3}$ and $t_0 \approx 16, (19), [19]$ days , $s_{\rm e} = 0.37, (0.42), [0.5]$ for $Y_e < 0.22, \forall s_0$; $(Y_e > 0.22, \frac{s_0}{k_b/\rm baryon} > 55)$; [$Y_e < 0.22, \frac{s_0}{k_b/\rm baryon} < 55$]. The accuracy of the analytic approximation is within $\sim 20\%$, which is comparable to the uncertainty due to nuclear mass model and reaction rates uncertainties. The shallower than square-root dependence on ρt^3, $s_{\rm e} \leq 1/2$, results from an increase with time of the characteristic e$^{\pm}$ energy $\langle E_{\rm e} \rangle$ (in contrast with the commonly used $\langle E_{\rm e} \rangle \propto t^{-1/3}$). This occurs due to the activity of "inverted decay-chains" in which a slow, low-energy decay is followed by a fast, high-energy one. Our results imply that the identification of "thermalization breaks" in bolometric kilonova light-curves may be used to determine the ratio M/v^3 of ejecta mass and velocity, as is done for Ia SNe using the γ-ray thermalization break. We provide an analytic description of the time dependent electron deposition efficiency that may be straightforwardly implemented in kilonovae light-curve calculations, and is accurate to within a factor ~ 2 over $3-4$ orders of magnitude in energy deposition evolution. Finally, we show that our results are weakly dependent on nuclear physics uncertainties.

Speaker: Ben Shenhar (Weizmann Institute of Science)

12:40 PM → 2:00 PM **Lunch break** 1h 20m

2:00 PM → 3:00 PM **Thursday afternoon: Block 1**

2:00 PM

Discussion 1h

Speakers: Paul Barklem (Uppsala University) , Stuart Sim (Queen's University Belfast)