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The Origin of Outflows in Evolved Stars

Edited by

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THE ORIGIN OF OUTFLOWS IN EVOLVED STARS

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COVER ILLUSTRATION: HIDDEN IN STARDUST (Katrien Kolenberg)

Astrophysics has many mysteries yet to reveal. Red giants are old stars that eject gaseous material and solid particles through a stellar wind. Some red giants appeared to lose an exceptionally large amount of mass this way. However, new observations reveal that this is not quite the case. The stellar wind is not more intense than normal, but is affected by a partner that was overlooked until now: a second star that circles the red giant. Many old stars do not die alone. The ejected material by the red giant will form the basis for new stars, planetary systems and ultimately possibly life. In this Universe we, Humans, are contemplating our own cosmic origins. We are indeed made of stardust.

This work, created by Prof. Katrien Kolenberg, was made in a series to illustrate the research paper by colleagues Decin et al. (2019), published by Nature Astronomy in February 2019. A painting from this series. "Blown away by binary interaction", was published on the cover of Nature Astronomy in May 2019.

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THE ORIGIN OF OUTFLOWS IN EVOLVED STARS

PROCEEDINGS OF THE 366th SYMPOSIUM OF THE INTERNATIONAL ASTRONOMICAL UNION VIRTUAL MEETING, INITIALLY PLANNED FOR LEUVEN, BELGIUM 1–6 NOVEMBER, 2021

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Preface

The prime parameter determining the evolution of a star is its mass. Any modification to the stellar mass over time has large repercussions on its evolutionary path. Both low-mass and massive stars are known to power strong stellar winds at the end of their life. Such winds carry away both mass and momentum from the star's surface, with rates that vary as a function of stellar luminosity, evolutionary phase, and chemical composition (i.e. metallicity). Binary mass transfer is another important mode of mass loss. The mass-loss rate determines the type of the stellar end product and the amount by which these stars contribute to the chemical enrichment of the interstellar medium, hence providing the building blocks of planets and life. A proper understanding of stellar evolution and of the chemical make-up of the building blocks in the Universe near and far can thus not be achieved without a detailed understanding of the wind physics during the late stages of stellar evolution as a function of the cosmic environment and hence metallicity. The goal of this IAUS366 symposium is to propel our understanding of stellar wind physics across stellar mass by bringing together the scientific communities which often focus on either the low-mass or the massive stars. This cross-disciplinary approach will fuel new scientific ideas and insights and will facilitate for new collaborations to grow across communities.

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Over the past decades, we have witnessed an enormous progress in our understanding of mass loss through stellar winds and binary interaction. Stellar winds govern the evolution during crucial phases of all stars in the universe. The driving force to counteract stellar gravity so that a wind can be launched has been identified for various regions in the Hertzsprung-Russell diagram, including the gas pressure gradient, radiation pressure on metal lines or on dust species, magnetic pressure etc. Although these forces have been established, various factors influencing or even key to the on set of the stellar wind remain elusive. For massive stars, we recall the ground-breaking detection of the first gravitational wave event in September 2015, which was caused by the merging of a binary black hole system with surprisingly high inferred masses, indicating our limited understanding of winds of massive stars. For low mass stars, an esteemed example is the current inability of scientists to predict which little dust seeds will be the first to form when the star is on the Asymptotic Giant Branch (AGB), as a result of which a stellar wind will be launched. As of today, we still do not know the mass-loss rate and the wind velocity that our own Sun will have once it becomes an AGB star. This incomprehension has direct consequences for any evolution model that studies the chances for Earth to survive (or not) the solar AGB evolution.

The outflows of low-mass and massive stars share various similarities, as well as profound differences. Through their winds, evolved low-mass and massive stars are the dominant sources for the chemical enrichment of the interstellar medium. Key species such as carbon, nitrogen, and oxygen are synthesized in the core of low-mass stars with the s-process being responsible for approximately half the atomic nuclei heavier than iron. In massive stars, the temperature and pressure in the core can reach high enough values for fusion of carbon, oxygen, and then even heavier elements like neon, magnesium, and silicon. Low-mass stars will slowly eject their atmosphere via a stellar wind, transiting through the post-AGB phase into a planetary nebula. Massive stars eject mass via a fast stellar outflow and finally via a supernova explosion, the latter potentially providing one of the sources for r-process elements. While chemical elements are further processed into a large variety of molecules and dust species in the stellar outflows of low-mass stars, an analogous chemistry does not occur in the winds of massive stars. The wind driving mechanism between low-mass and massive stars is also highly different with atomic line driving being the cause for the winds of massive stars, dust continuum driving for low-mass stars, and potentially molecular line driving for red supergiant winds. And while the dynamical chemistry seems highly different in low-mass and massive evolved stars, their outflows share various common characteristics including non-local thermodynamic equilibrium conditions, density inhomogeneities, radiative forces and hence acceleration, creation of bow shocks at the interface with the interstellar medium, etc.

Recent observations provide support for 50-90% of all stars being part of a binary (or multiple) system. Binary interaction impacts the evolution of stars and hence can play a decisive role for the stellar end product that is produced. The gravitational waves produced by colliding black holes or neutron stars are one example touching on massive star evolution. Recent high spatial resolution observations also have set aside the long-standing idea that the winds of low-mass stars are spherically symmetric with clear evidence of stellar and planetary companions shaping the wind's morphology.

New observational capabilities were key for a lot of progress in our understanding of stellar winds. Data obtained with MUSE, X-Shooter, Hubble etc. allowed for determining the strong mechanical and radiative feedback from massive stars on their host environments and for scrutinizing the role of density inhomogeneities on the retrieval of wind parameters across metallicity. The study of the winds around low-mass stars has seen an upheaval thanks to new instrumentation allowing for astrochemistry to play a decisive role. Astrochemistry provides us with unique tools to disentangle the phase-transition of atoms to small molecules and larger dust grains in environments unlike any terrestrial laboratories. Data obtained with ALMA, VLB(I), PdBI, SMA, VLT(I) etc. provide us with crucial information to disentangle the prevailing chemical processes occurring in stellar atmospheres, stellar winds, and the surrounding medium. The study of molecular and dust absorption and emission is a key technique in modern astrophysics, particularly through the ability to probe physical environments otherwise hidden from view.

Along with new instrumentation came new developments in HPC facilities allowing for more sophisticated numerical models describing stellar winds. Integrating the highly different timescales involved in various facets of stellar wind physics and chemistry into a unified wind model requires clever use of parallelization and memory sharing. Time-dependent radiation-driven wind models have reached a mature state, although the change from a 1D to a full 3D geometry remains challenging. An analogous challenge holds for incorporating non-equilibrium gas-phase cluster formation in low-mass wind models. As such, models including all aspects related to hydrodynamics, chemistry, and radiation cannot yet be used to directly retrieve parameters from observations, but they serve a key role for proposing more simplified (analytical) wind models and for the a-posteriori interpretation of the observables. New theoretical wind models developed during last few years allowed for some crucial aspects in stellar winds physics to be elucidated and serve as a guide for new instrumentation to be developed.

In view of the exciting new and unexpected results from facilities such as ALMA, VLB(I), PdBI, SMA, VLT(I), MUSE, X-Shooter, GAIA etc. which challenge our understanding of the dominant physical and chemical processes in evolved star's outflows, it was timely to hold an IAU Symposium centring on this theme. Historically, IAU symposia have focused on one of the various classes of evolved stars exhibiting strong stellar winds and their contribution to the galactic evolution. In the past 30 years, there have been 18 Symposia devoted to Massive stars and Supernovae, 7 Symposia on Planetary Nebulae, 3 Symposia on AGB stars, and none specifically oriented toward post-AGB or red supergiant stars. However, no IAU symposium had yet focused on the outflows from evolved stars across stellar mass. As such, common ground on which significant progress can build had remained invisible, and hence not explored. Examples include new diagnostic and numerical methodologies of moving from a 1D to a 3D morphology, dealing with an ensemble of atomic/molecular lines, accurate assessment of radiative forces, solving coupled differential equations, exploiting current HPC facilities, diagnostic tools from detailed observations, statistical model fitting tools, retrieval and forward modelling, optimal use of current and future observing facilities etc. This IAU symposium aimed to bridge the various communities dealing with the outflows of evolved stars with the prime goal being the creation of breeding grounds for new ideas to arise and new collaborations to grow across communities. As such, discussion sessions, education and training were a crucial part of this symposium.

The IAUS366 symposium was endorsed and sponsored by the IAU Division G Steering Committee, with support from the IAU Divisions B, C, and H. The IAU Executive Committee approved the symposium in December 2018. It is a also great pleasure to acknowledge the financial support of our sponsors the ERC and the KU Leuven, and the active support of the members of the SOC and LOC in realizing the numerous details always associated with such a symposium.

This symposium materialized into 7 invited review talks, 6 invited talks, 45 contributed talks, 31 poster papers, and 15 pitch talks, stimulating discussion among some 330 astronomers from 49 countries. May these Proceedings be a scientific reflection of our current knowledge of the outflows of evolved stars and shape a creative research landscape where new ideas arise and enigmas are solved.

Leen Decin chair SOC
Clio Gielen, chair LOC
Leuven, Belgium, 1 November 2021

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Address by the Scientific and Local Organizing Committee

Dear colleagues,

It is with great pleasure that I welcome you all to this long-awaited IAU symposium, the IAUS366 that will discuss *The Origin of Outflows in Evolved Stars*. It would have been with even more pleasure if I could have welcomed you all in person, here in Leuven, as originally planned. We tried to escape the impact of the COVID-19 pandemic by moving the symposium from October 2020 to November 2021. But alas, also now we had to decide to change the format of the meeting from an in-person meeting to a virtual conference. As my colleagues of the SOC and LOC can testify, I was the last person accepting that we had to make this inevitable move. It was the only way forward for inclusion at all levels to be guaranteed, since not all countries around the world have the same success-rate in their vaccination strategy. Inclusion and diversity are key elements of this IAUS366 symposium – as you will also see reflected in its rich scientific program. I am proud that I can welcome today some 350 participants from all over the world. Junior and senior scientists, female and male with a diverse ethnic background. It is with pain in the heart that I can't welcome you in person, that I can't show you the nice city of Leuven with its rich history where we planned the symposium to take place, that I can't just take a coffee and chat and discuss with you in person during one of the breaks. It is thanks to the incredibly hard work of the LOC, in particular during these last few weeks, that we could change the format from a live meeting to a virtual one, in a format of which we think is the best to reach you all, to debate science, to foster discussion, to offer excellent training sessions, to let you enjoy the sometimes serendipitous gatherings in Gather Town where you can meet new colleagues.

The idea for this IAU symposium was given birth in my ERC-CoG application aerosol (no. 646758)†. That ERC grant is focussing on the origin of outflows in cool, evolved, low and intermediate-mass stars. It was one of the scientific outcomes of that ERC grant (Decin et al. 2019) which was translated by our colleague and artist Katrien Kolenberg into the very nice painting which we proudly use as cover page for this IAU proceedings, and which was used for the creation of the banner for the IAUS366 website‡. The arts offer a unique way of science communication, of reaching out to the society, of fostering a transdisciplinary discussion beyond our disciplinary silos and so of stimulating creative thinking. I believe that interdisciplinary, and even more transdisciplinary, collaborations are *a conditio sine qua non* for answering the 21st century questions.

This statement is also of relevance even if we stay within our restricted field of astrophysics' research, where we often tend to stay too often, too easily in our comfort zone. Not only do low-and intermediate mass stars lose a substantial fraction of their mass at the end of their life, the same holds true for massive stars. As outlined in the Preface, the outflows of low-mass and massive stars share various similarities and differences. For that reason, we decided to cross and bridge these disciplines to foster cross-fertilization between the research domains of low-mass and massive stars. For that reason, this IAU symposium is also financially supported by a KU Leuven C1 excellence grant, entitled maestro§, which focusses on massive star outflows. The financial support by the ERC and the KU Leuven allows us to offer you this week a symposium on the outflows from evolved stars across stellar mass, a unicum. This IAU symposium aims to bridge the various communities dealing with the outflows of evolved stars with the prime goal being

† https://fys.kuleuven.be/ster/research-projects/aerosol
‡ https://iaus366.be
§ https://fys.kuleuven.be/ster/research-projects/maestro

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the creation of breeding grounds for new ideas to arise and new collaborations to grow across communities. As such, discussion sessions and education are a crucial part of this symposium.

We had identified a number of themes to be contained in this 5-days program, each taking roughly 1/2 day. However, the fact that the meeting is now online, and that we wished to accommodate for different time zones made us shuffle the themes across one another; this is also a way of bridging communities. The selection of the daily conference hours was done by weighting with the number of participants from different continents. We apologize if this is not always the most convenient hours for you to attend, but it was the best way for guaranteeing inclusion. Therefore the meeting will be fully recorded to allow you watching some sessions at more appropriate timings.

The same holds true for the skills training sessions which are offered during the symposium. Actually, some excellent sessions were already offered earlier today. I know, one could suggest it would have been more appropriate to welcome you before the start of these first training sessions. However, today 6 pm CET, seemed to us the best timing to reach most of you worldwide, from east to west. Life is never perfect. To continue on that aspect of training, I wish to express my sincere gratitude to all people who have agreed to prepare trainings which tackle a wide range of skills, from numerical modeling to observations, from didactics to career advice. That training is essential to all of us, junior and senior.

There is also time foreseen for social gathering. Yes, I know, it would have been more pleasant if we could have done that with some marvelous Belgian beers and delicious Belgian chocolates and that within the historical city of Leuven which is home to the oldest university of the low countries, inaugurated in 1425 -almost 600 years ago. If you once happen to be in Leuven in the future, I promise to indulge you with these Belgian pleasures. The alternative I can offer this week can be -apologies for that -fully categorized as being non-gastronomic. The LOC has created a Gather Town environment where we can meet ... virtually. Indeed, non-gastronomic but a poll amongst scientists during these COVID-19 times indicates that this virtual environment is often felt to have lower barriers for junior scientists to (virtually) walk to more senior scientists to get into contact. Let's remember the famous Monty Python lyrics 'Always look on the bright side of life'.

And let us now turn again our attention to the rich scientific program that this IAUS366 offers to you. We are honoured by the fact that excellent junior and senior scientists accepted our request for a review or invited talk. We are proud of the numerous submissions for contributed talks, of which we could only select a fraction. That selection was based on an anonymous process. Without knowledge of the identity, seniority, gender of the applicants, the SOC members judged independently the submitted abstracts. The highest ranked abstracts were selected as contributed talks. The outcome of this anonymous selection procedure is also a very nice balance between junior and senior scientists, between male and female scientists across nationalities; something of which I am very proud. In addition, there is a very nice selection of posters which will be displayed via Gather Town. Being an IAU Symposium, the creation of a proceedings book is an integral part of its concept; the result proving the stimulating scientific outcome of the IAUS366 symposium.

Having said this all, there remain two important things to be said. Firstly, I wish to thank my SOC colleagues. I thank them for their scientific advice on all kind of matters starting with shaping the program and submitting the application to the IAU in 2018 to the final selection of speakers. An even greater thanks goes to the LOC. In this challenging COVID-19 times where the rules are continuously changing, these people have been required and have been very flexible to continuously change plans. From in-person to post-poned, to again in-person, and finally virtually. It will not surprise you that my greatest thank goes to Clio Gielen, the chair of the LOC, the person behind the email address iausleuven@kuleuven.be. Only during these last 4 months, we have exchanged above 400 emails and had numerous online and in-person meetings. And this is not counting for the >1000 emails that Clio received from all of you on all kind of organizational matters. Clio, without you, this symposium would not have seen light. The saying is 'Behind every strong man there is a strong woman'. It will not surprise you that I don't like the gender-inequality in this saying and therefore wishes to adapt it to 'Behind every strong person there is another strong person'; and this is you, for the IAUS366 symposium and for our Institute of Astronomy in Leuven.

It is with great pleasure that I finally declare open the IAU symposium no. 366 - *The origin of Outflows in Evolved Stars*. I am honoured and proud to be your chairwoman for this symposium. I wish you all a very constructive and pleasant five working days.

Leen Decin, chair SOC
Clio Gielen, chair SOC
Leuven, Belgium, 1 November 2021

Reference

Decin L., Homan W., Danilovich T., et al. 2019, Nature Astromomy 3, 408

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