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Winds of Stars and Exoplanets

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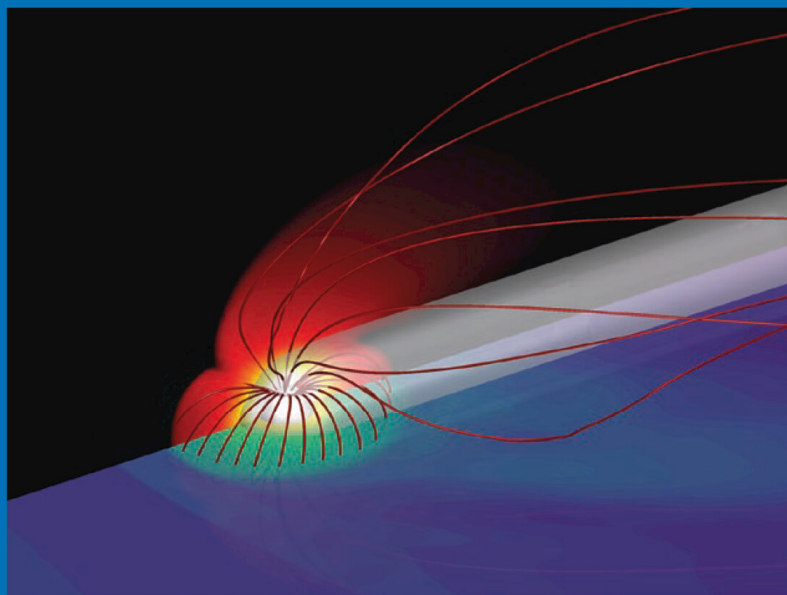
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COVER ILLUSTRATION:

Three-dimensional simulation of the escaping atmosphere of a close-in exoplanet interacting with the wind of its host star. The red field lines represent the planetary magnetic field, while the contours represent the total density (horizontal plane) and the neutral hydrogen density (vertical plane). Figure from Carolan et al 2021.

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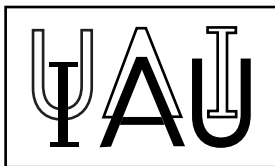
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WINDS OF STARS AND EXOPLANETS

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THE INTERNATIONAL ASTRONOMICAL UNION
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Table of Contents

Preface	ix
Editors	xi
List of Contributors	xii

Part 1: Overview of Winds of stars and exoplanets

Winds and magnetospheres from stars and planets: similarities and differences	3
<i>Stan Owocki</i>	

Part 2: Observational evidence of winds

Observations of Winds and CMEs of Low-Mass Stars	25
<i>Rachel A. Osten</i>	
Observations of outflows of massive stars	37
<i>Andrea Mehner</i>	
Observations of planetary winds and outflows	56
<i>Leonardo A. Dos Santos</i>	
The effect of winds in red supergiants: modeling for interferometry	72
<i>Gemma González-Torà, Markus Wittkowski, Ben Davies and Bertrand Plez</i>	
The porous envelope and circumstellar wind matter of the closest carbon star, CW Leonis	78
<i>Hyosun Kim, Ho-Gyu Lee, Youichi Ohyama, Ji Hoon Kim, Peter Scicluna, You-Hua Chu, Nicolas Mauron and Toshiya Ueta</i>	
Is the magnetospheric accretion active in the Herbig Ae/Be stars?	84
<i>Giovanni Pinzón, Jesús Hernández and Javier Serna</i>	
Short-term variations of surface magnetism and prominences of the young sun-like star V530 Per	89
<i>Cang Tianqi, Pascal Petit, Jean-François Donati and Colin Folsom</i>	
Water and silicon-monoxide masers monitored towards the “water fountain” sources	91
<i>H. Imai, K. Amada, J. F. Gómez, L. Uscanga, D. Tafoya, K. Nakashima, K.-Y. Shum, Y. Hamae, R. Burns and G. Orosz</i>	
Weakening the wind with ULLYSES: Examining the Bi-Stability Jump	94
<i>Olivier Verhamme and Jon Olof Sundqvist</i>	
Statistical properties of cold circumstellar envelopes observed in NESS–NRO	97
<i>K. Amada, S. Fukaya, H. Imai, P. Scicluna, N. Hirano, A. Trejo-Cruz, S. Zeegers, F. Kemper, S. Srinivasan, S. Wallström, T. Dharmawardena and H. Shinnaga</i>	

Part 3: Physical ingredients of winds

The origin of planetary winds	103
<i>Daria Kubyshkina</i>	
Stellar wind from low-mass main-sequence stars: an overview of theoretical models	122
<i>Munehito Shoda</i>	
The Driving of Hot Star Winds	130
<i>Andreas A.C. Sander</i>	
Slingshot Prominences, Formation, Ejection and Cycle Frequency in Cool Stars	144
<i>S. Daley-Yates and M. M. Jardine</i>	
Effect of stellar flares and coronal mass ejections on the atmospheric escape from hot Jupiters	148
<i>Gopal Hazra, Aline A. Vidotto, Stephen Carolan, Carolina Villarreal D'Angelo and Ward Manchester</i>	
Physics of the atmospheric escape driven by EUV photoionization heating: Classification of the hydrodynamic escape in close-in planets	155
<i>Hiroto Mitani, Riouhei Nakatani and Naoki Yoshida</i>	
Discrete Absorption Components from 3-D spot models of hot star winds	161
<i>F. A. Driessen and N. D. Kee</i>	
Hydrodynamic disk solutions for Be stars using HDUST	168
<i>C. Arcos, M. Curé, I. Araya, A. Rubio and A. Carciofi</i>	
Role of Longitudinal Waves in Alfvén-wave-driven Solar/Stellar Wind	174
<i>Kimihiko Shimizu, Munehito Shoda and Takeru K. Suzuki</i>	
ISOSCELES: Grid of stellar atmosphere and hydrodynamic models of massive stars. The first results	180
<i>Ignacio Araya, Michel Curé, Natalia Machuca and Catalina Arcos</i>	
Quantification of the environment of cool stars using numerical simulations	185
<i>J. J. Chebly, Julián D. Alvarado-Gómez and Katja Poppenhaeger</i>	
Hydrodynamic solutions of radiation driven wind from hot stars	191
<i>M. Curé, I. Araya, C. Arcos, N. Machuca and A. Rodriguez</i>	
Gap opening by planets in discs with magnetised winds	194
<i>Vardan Elbakyan, Yinhao Wu, Sergei Nayakshin and Giovanni Rosotti</i>	
Solar Wind and Hydrologic Cycle	196
<i>Xuguang Leng</i>	
Magnetic confinement in the wind of low mass stars	198
<i>Rose F. P. Waugh and Moira M. Jardine</i>	

Clumping and X-rays in cool B Supergiants	200
<i>Matheus Bernini-Peron, W. L. F. Marcolino and A. A. C. Sander</i>	
Part 4: Flow-flow interactions	
Interaction between massive star winds and the interstellar medium	205
<i>Jonathan Mackey</i>	
Numerical Modeling of Galactic Superwinds with Time-evolving Stellar Feedback	217
<i>A. Danekkar, M. S. Oey and W. J. Gray</i>	
Winds of OB stars: impact of metallicity, rotation and binary interaction	223
<i>Varsha Ramachandran</i>	
X-ray view of colliding winds in WR 25	230
<i>Bharti Arora, Jeewan C. Pandey and Michaël De Becker</i>	
Double tail structure in escaping atmospheres of magnetised close-in planets	232
<i>A. A. Vidotto, S. Carolan, G. Hazra, C. Villarreal D'Angelo and D. Kubyskhina</i>	
Shock breakout in winds of red supergiants: Type IIP supernovae	235
<i>Alak Ray, Harita Palani Balaji, Adarsh Raghu and Gururaj Wagle</i>	
On the making of a PN: the interaction of a multiple stellar wind with the ISM	238
<i>Arturo Manchado, Eva Villaver, G. García-Segura and Luciana Bianchi</i>	
Part 5: Relevance of winds on stellar/planetary evolution	
Role of planetary winds in planet evolution and population	243
<i>D. Modirrousta-Galian</i>	
Size Evolution and Orbital Architecture of KEPLER Small Planets through Giant Impacts and Photoevaporation	251
<i>Gu Pin-Gao, Matsumoto Yuji, Kokubo Eiichiro and Kurosaki Kenji</i>	
Spin-down and reduced mass loss in early-type stars with large-scale magnetic fields	257
<i>Z. Keszthelyi, A. de Koter, Y. Götzberg, G. Meynet, S.A. Brands, V. Petit, M. Carrington, A. David-Uraz, S.T. Geen, C. Georgy, R. Hirschi, J. Puls, K.J. Ramalatswa, M.E. Shultz and A. ud-Doula</i>	
Mass loss implementation and temperature evolution of very massive stars	263
<i>Gautham N. Sabhahit, Jorick S. Vink, Erin R. Higgins and Andreas A.C. Sander</i>	
The Evolution of Atmospheric Escape of Highly Irradiated Gassy Exoplanets	269
<i>Andrew P. Allan, Aline A. Vidotto and Leonardo A. Dos Santos</i>	

The future of Jupiter-like planets around Sun-like stars: first steps	275
<i>T. Konings, R. Baeyens and L. Decin</i>	
Rapid orbital precession of the eclipsing binary HS Hydrae	278
<i>A. M. Matekov and A. S. Hojaev</i>	
To the dynamics of the two-body problem with variable masses in the presence of reactive forces	281
<i>A.T. Ibraimova and M.Zh Minglibayev</i>	
Evolution equations of the multi-planetary problem with variable masses	283
<i>A.B. Kosherbayeva and M.Zh Minglibayev</i>	
Planet migration in accretion discs in binary systems	285
<i>A.D. Nekrasov, S.B. Popov and V.V. Zhuravlev</i>	
Signatures of wind formation in optical spectra of precursors of planetary nebulae	287
<i>Kārlis Puķītis and Laimons Začs</i>	
Author Index	289

Evolution equations of the multi-planetary problem with variable masses

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Abstract. We investigated the influence of the variability of the masses of planets and the parent star on the dynamic evolution of n planetary systems, considering that the masses of bodies change isotropically with different rates. The methods of canonical perturbation theory, which developed on the basis of aperiodic motion over a quasi-conical cross section and methods of computer algebra were used. $4n$ evolutionary equations were obtained in analogues of Poincare elements. As an example, the evolutionary equations of the three-planet exosystem $K2 - 3$ were obtained explicitly, which is a system of 12 linear non-autonomous differential equations. Further, the evolutionary equations will be investigated numerically.

Keywords. celestial mechanics, variable mass, analogues of Poincare elements, multi-planetary system, secular perturbation.

1. Introduction

To date, there are more than 5,000 confirmed exoplanets and more than 3,800 planetary systems in the [NASA \(2022\)](#) database. To research exoplanetary systems in the non-stationary stage of their evolution is represented important interest.

2. Problem statement

We considered the problem of $n + 1$ bodies with variable masses $m_0 = m_0(t)$ – mass of the parent star S , $m_i = m_i(t)$, – the mass of the planet P_i . The laws of mass are known and given functions of time $m_0 = m_0(t)$, $m_1 = m_1(t), \dots, m_n = m_n(t)$, ($n \geq 3$). The masses of spherical symmetric bodies change isotropically with different rates $\dot{m}_0/m_0 \neq \dot{m}_i/m_i$, $\dot{m}_i/m_i \neq \dot{m}_j/m_j$ $i, j = 1, 2, \dots, n$, $i \neq j$.

Differential equations of motion of n bodies with isotropically varying masses in a relative coordinate system are given in [Minglibaev \(2012\)](#)

$$\ddot{\vec{r}}_i = -f \frac{(m_0 + m_i)}{r_i^3} \vec{r}_i + f \sum_{j=1}^n m_j \left(\frac{\vec{r}_j - \vec{r}_i}{r_{ij}^3} - \frac{\vec{r}_j}{r_j^3} \right), \quad (i, j = 1, 2, \dots, n), \quad (2.1)$$

where $r_{ij} = r_{ji} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2}$ – mutual distances of the center of spherical bodies, f – gravitational constant, $\vec{r}_i(x_i, y_i, z_i)$ – the radius-vector of center of the planet P_i , the sign "stroke" when summing means that $i \neq j$.

For our purposes, analogues of the second system of canonical Poincare elements are preferred

$$\Lambda_i, \lambda_i, \xi_i, \eta_i, p_i, q_i, \quad (2.2)$$

which are introduced on the basis of elements of aperiodic motion over a quasi-conical cross section [Minglibaev \(2012\)](#)

3. Evolutionary equations of n planets with variable masses

The evolutionary equations of n planets with variable masses in dimensionless variables (2.2)-(2.5) in the non-resonant case have the form in our work Prokopenya et al. (2022)

$$\xi'_i = \sum_{s=1}^{i-1} m_s \left(\frac{\Pi_{ii}^{is}}{\Lambda_i} \eta_i + \frac{\Pi_{is}^{is}}{\sqrt{\Lambda_i \Lambda_s}} \eta_s \right) + \sum_{k=i+1}^n m_k \left(\frac{\Pi_{kk}^{ik}}{\Lambda_i} \eta_i + \frac{\Pi_{ik}^{ik}}{\sqrt{\Lambda_i \Lambda_k}} \eta_k \right) - \frac{3\gamma''_i \Lambda_i^3}{2\gamma_i \mu_{i0}^2} \eta_i, \quad (3.1)$$

$$\eta'_i = - \sum_{s=1}^{i-1} m_s \left(\frac{\Pi_{ii}^{is}}{\Lambda_i} \xi_i + \frac{\Pi_{is}^{is}}{\sqrt{\Lambda_i \Lambda_s}} \xi_s \right) - \sum_{k=i+1}^n m_k \left(\frac{\Pi_{kk}^{ik}}{\Lambda_i} \xi_i + \frac{\Pi_{ik}^{ik}}{\sqrt{\Lambda_i \Lambda_k}} \xi_k \right) + \frac{3\gamma''_i \Lambda_i^3}{2\gamma_i \mu_{i0}^2} \xi_i, \quad (3.2)$$

$$p'_i = - \sum_{s=1}^{i-1} m_s B_1^{is} \left(\frac{q_i}{4\Lambda_i} - \frac{q_s}{4\sqrt{\Lambda_i \Lambda_s}} \right) - \sum_{k=i+1}^n m_k B_1^{ik} \left(\frac{q_i}{4\Lambda_i} - \frac{q_k}{4\sqrt{\Lambda_i \Lambda_k}} \right), \quad (3.3)$$

$$q'_i = \sum_{s=1}^{i-1} m_s B_1^{is} \left(\frac{p_i}{4\Lambda_i} - \frac{p_s}{4\sqrt{\Lambda_i \Lambda_s}} \right) + \sum_{k=i+1}^n m_k B_1^{ik} \left(\frac{p_i}{4\Lambda_i} - \frac{p_k}{4\sqrt{\Lambda_i \Lambda_k}} \right). \quad (3.4)$$

At the same time, the expressions Π_{ii}^{is} , Π_{is}^{is} , Π_{kk}^{ik} , Π_{ik}^{ik} in equations (3.1) - (3.4) and the Laplace coefficients retain their form, but they are already dimensionless quantities. All notations are given in the article Prokopenya et al. (2022).

4. The evolutionary equations of the three-planet exosystem $K2 - 3$ in explicit form

As an example, the case of $n = 3$ was considered. The evolutionary equations (3.1)–(3.4) for the $K2 - 3$ exosystem are described by a system of 12 linear non-autonomous differential equations, which are obtained explicitly. The resulting system splits into two subsystems for eccentric and oblique elements. The resulting equations of secular perturbations are difficult, so they will be investigated numerically.

5. Conclusion

The evolutionary equations of a multi-planetary problem with isotropically varying masses at different rates in analogues of osculating Poincare elements were obtained. These evolutionary equations can be used for any n planetary problem with variable masses. The evolutionary equations for the $K2 - 3$ exosystem were written explicitly. The obtained evolutionary equations will be investigated numerically.

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Author index

- Allan, A. P. – 269
Alvarado-Gómez, J. D. – 185
Amada, K. – 91, 97
Araya, I. – 168, 180, 191
Arcos, C. – 168, 180, 191
Arora, B. – 230
- Baeyens, R. – 275
Balaji, H. P. – 235
Bernini-Peron, M. – 200
Bianchi, L. – 238
Brands, S. A. – 257
Burns, R. – 91
- Carciofi, A. – 168
Carolan, S. – 148, 232
Carrington, M. – 257
Chebly, J. J. – 185
Chu, Y.-H. – 78
Curé, M. – 168, 180, 191
- Daley-Yates, S. – 144
Danekar, A. – 217
David-Uraz, A. – 257
Davies, B. – 72
De Becker, M. – 230
de Koter, A. – 257
Decin, L. – 275
Dharmawardena, T. – 97
Donati, J.-F. – 89
Dos Santos, L. A. – 56, 269
Driessen, F. A. – 161
- Eiichiro, K. – 251
Elbakyan, V. – 194
- Folsom, C. – 89
Fukaya, S. – 97
- García-Segura, G. – 238
Geen, S. T. – 257
Georgy, C. – 257
Gómez, J. F. – 91
González-Torà, G. – 72
Götberg, Y. – 257
Gray, W. J. – 217
- Hamae, Y. – 91
Hazra, G. – 148, 232
Hernández, J. – 84
Higgins, E. R. – 263
- Hirano, N. – 97
Hirschi, R. – 257
Hojaev, A. S. – 278
- Ibraimova, A. T. – 281
Imai, H. – 91, 97
- Jardine, M. M. – 144, 198
- Kee, N. D. – 161
Kemper, F. – 97
Kenji, K. – 251
Keszthelyi, Z. – 257
Kim, H. – 78
Kim, J. H. – 78
Konings, T. – 275
Kosherbayeva, A. B. – 283
Kubyshkina, D. – 103, 232
- Lee, H.-G. – 78
Leng, X. – 196
- Machuca, N. – 180, 191
Mackey, J. – 205
Manchado, A. – 238
Manchester, W. – 148
Marcolino, W. L. F. – 200
Matekov, A. M. – 278
Mauron, N. – 78
Mehner, A. – 37
Meynet, G. – 257
Minglibayev, M. Z. – 281, 283
Mitani, H. – 155
Modirrousta-Galian, D. – 243
- Nakashima, K. – 91
Nakatani, R. – 155
Nayakshin, S. – 194
Nekrasov, A. D. – 285
- Oey, M. S. – 217
Ohyama, Y. – 78
Orosz, G. – 91
Osten, R. A. – 25
Owoccki, S. – 3
- Pandey, J. C. – 230
Petit, P. – 89
Petit, V. – 257
Pin-Gao, G. – 251
Pinzón, G. – 84

- Plez, B. – 72
Popov, S. B. – 285
Poppenhaeger, K. – 185
Puķītis, K. – 287
Puls, J. – 257
- Raghu, A. – 235
Ramachandran, V. – 223
Ramalatswa, K. J. – 257
Ray, A. – 235
Rodriguez, A. – 191
Rosotti, G. – 194
Rubio, A. – 168
- Sabhahit, G. N. – 263
Sander, A. A. C. – 130, 200, 263
Sciicluna, P. – 78, 97
Serna, J. – 84
Shimizu, K. – 174
Shinnaga, H. – 97
Shoda, M. – 122, 174
Shultz, M. E. – 257
Shum, K.-Y. – 91
Srinivasan, S. – 97
Sundqvist, J. O. – 94
Suzuki, T. K. – 174
- Tafoya, D. – 91
Tianqi, C. – 89
Trejo-Cruz, A. – 97
- ud-Doula, A. – 257
Ueta, T. – 78
Uscanga, L. – 91
- Verhamme, O. – 94
Vidotto, A. A. – 148, 232, 269
Villarreal D'Angelo, C. – 148, 232
Villaver, E. – 238
Vink, J. S. – 263
- Wagle, G. – 235
Wallström, S. – 97
Waugh, R. F. P. – 198
Wittkowski, M. – 72
Wu, Y. – 194
- Yoshida, N. – 155
Yuji, M. – 251
- Začs, L. – 287
Zeegers, S. – 97
Zhuravlev, V. V. – 285