Relativistic Jet collimation and acceleration

Oliver Porth and Christian Fendt

Max Planck Institute for Astronomy, Heidelberg

Abstract

In the scenario of jet-formation suggested by Blandford & Payne (1982)[1] jets are launched as magnetised winds emanating from an accretion disk. As magnetised disks are found around a variety of jet-producing astrophysical objects from young stellar objects towards active galactic nuclei, the suggested disk-wind scenario can be seen as a unified picture of jet formation. We investigate how relativistic outflows become accelerated and collimated using the special relativistic Magneto-Hydro-Dynamics code Pluto 3[2]. Special focus is on the relativistic contribution to collimation „beyond the light-cylinder" and conversion of Poynting-flux into kinetic energy.

1 Blandford, R. D. & Payne, D. G. 1982, MNRAS, 199, 883
2 Mignone, A., Bodo, G., Massaglia, S., Matsakos, T., Tesileanu, O., Zanni, C., & Ferrari, A. 2007, ApJS, 170, 228

Ideal special relativistic MHD simulations

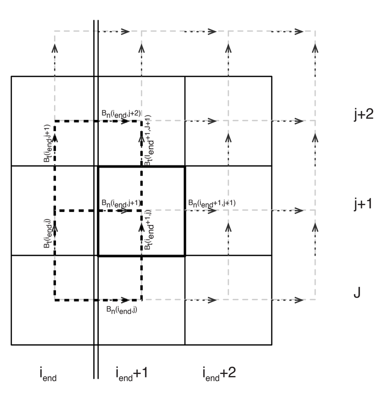
Jet material is highly ionized and thus well described as a neutral plasma no matter whether it is of hadronic or leptonic nature. Its high conductivity shortcuts any rest-frame electric current such that lab-frame electric fields reduce to $\mathbf{E} = \mathbf{B} \times \mathbf{v}$ (ideal MHD condition). As we are interested in the collimation and acceleration happening in scales of several hundred Schwarzschild radii, neglecting general relativistic effects is a fair approximation. Hence the current implementation treats gravity in the Newtonian approximation.
The omission of a constraining funnel-geometry and the inclusion of gravity differentiate the current study well from previous work for example by Komissarov et al. (2007)[1] .

1 Komissarov, S. S., Barkov, M. V., Vlahakis, N., & Königl, A. 2007, MNRAS, 380, 51

Initial Conditions & Injection Boundary

As initial state we prescribe a force-free magnetic corona ($F^{\alpha\beta}j_\beta = 0$) along with a gas distribution in hydrostatic equilibrium. Both is essential in order to avoid artificial relaxation processes caused by a non-equilibrium initial condition. We apply a polytropic equation of state $P = K\rho^\gamma$ with a polytropic index of $\gamma = 5/3$.
The disk-boundary represents the rotating Corona of a Keplerian accretion disk. In the case of a Scharzschild black hole, the innermost disk radius (the ISCO) $r_i = 3r_S$ has a rotational velocity of $v_\phi = 0.6c$. From the disk-corona, material is injected along the magnetic field-lines with an initial velocity of $v_z = 0.1 v_\phi(r)$, representing a slow disk-wind.

Outflow Boundaries



The usage of zero-current outflow boundaries minimizes spurious collimation of the low plasma-beta flow, where the dynamics is dominated by Lorentz-forces. Taking advantage of staggered magnetic fields, we have implemented a $\nabla \times \mathbf{B} = 0$ and $\nabla \cdot \mathbf{B} = 0$ boundary which is a substantial improvement over the standard procedure which creates artificially thin cylindrical flows.

Overview of Simulations

The free dynamical parameters of our SRMHD simulations are

- $v_K = v_\phi(r' = 1)$ the rotational velocity at the innermost disk-radius $r' = 1$
- $\beta_i = 8\pi \frac{P}{B_p^2}|_{r'=1}$ "Plasma-beta" as a measure for the strength of the magnetic fields.
- $v_{inj} = (v_z/v_\phi) \circ (z = 0, r)$ local injection speed in terms of the local Keplerian velocity as a control for the jet mass-loss rate.
- $\mu = -B'_\phi(z = 0, r') \cdot r'$ disk toroidal magnetic field strength as a handle on additional injection of Poynting-flux.

Using a stretched grid containing of 512x1024 cells which corresponds to a physical domain size of 300x600 r_S, we simulate for 500 Periods of the inner orbit, where a steady-state is usually reached after 200 Periods.
In the following we show a simulation with the parameters $(v_K, \beta_i, v_{inj}, \mu) = (0.5, 0.2, 0.1, 4)$ with a toroidal disk-field comparable to the poloidal field $B_\phi|_{r'=1} \simeq B_p|_{r'=1}$.

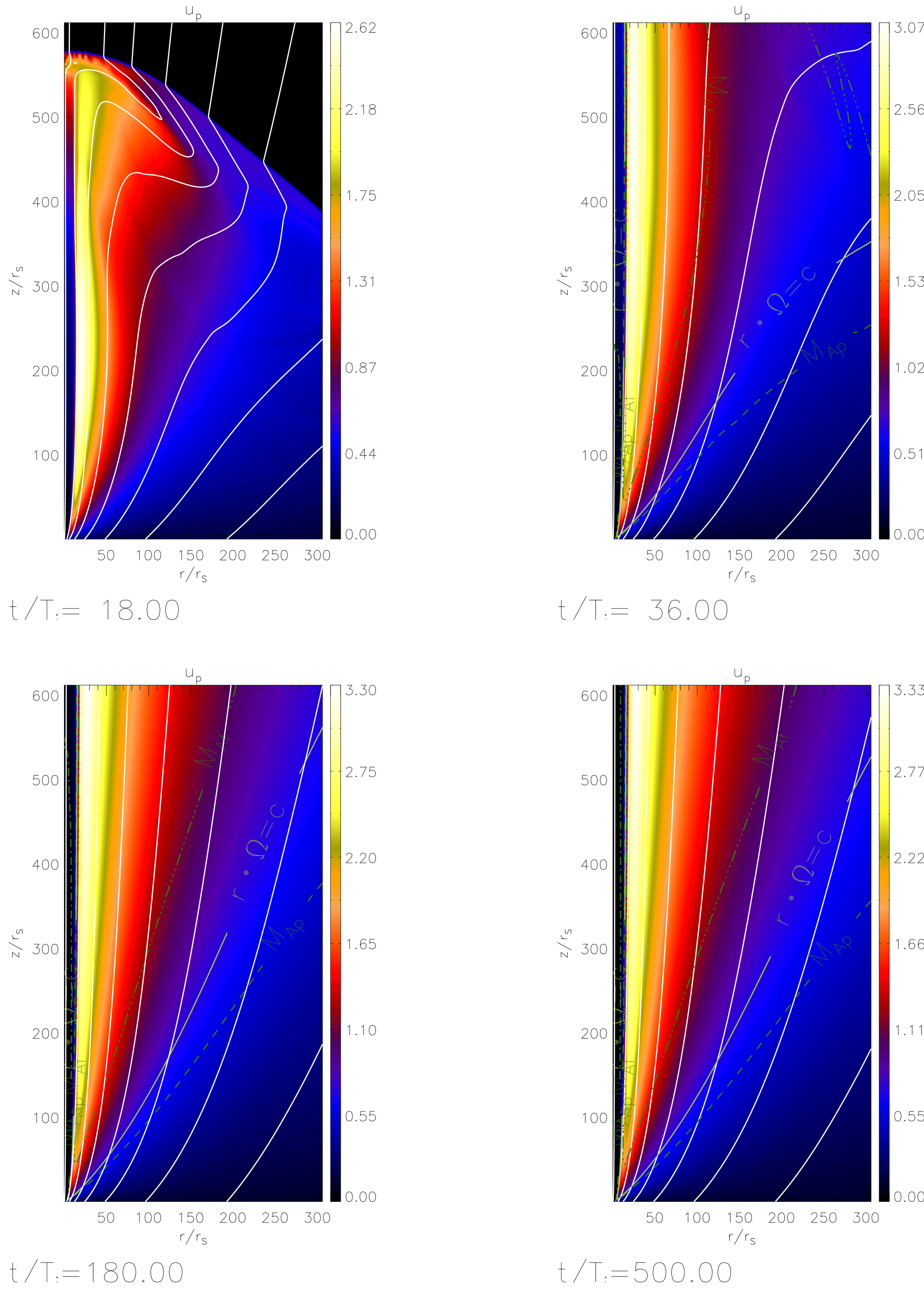
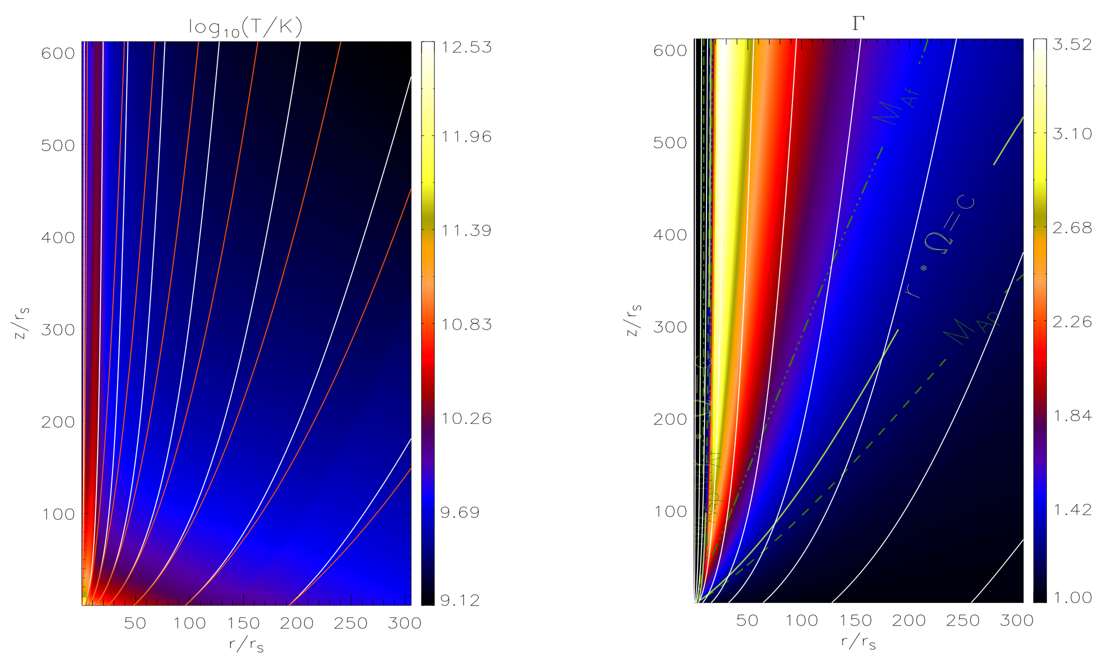


Figure 1:
Time series of fiducial simulation. Shown is poloidal velocity $u_p = \Gamma v_p$, field-lines (white) and critical surfaces.



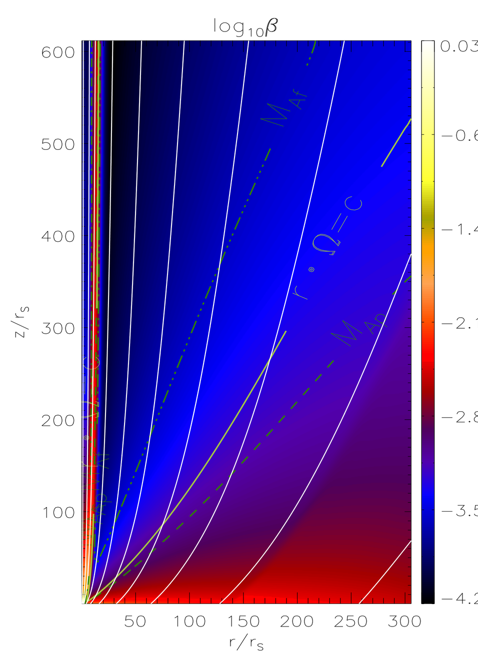


Figure 2:
Steady state of fiducial simulation. From upper left: Rest-frame temperature distribution in Kelvin with overplotted initial (red) and final (white) magnetic field-lines; Lorentz-factor with overplotted critical surfaces. The flow passes 1. the critical Alfvén surface, 2. the light-surface and 3. the fast-surface; Plasma-beta with the aforementioned overplots.

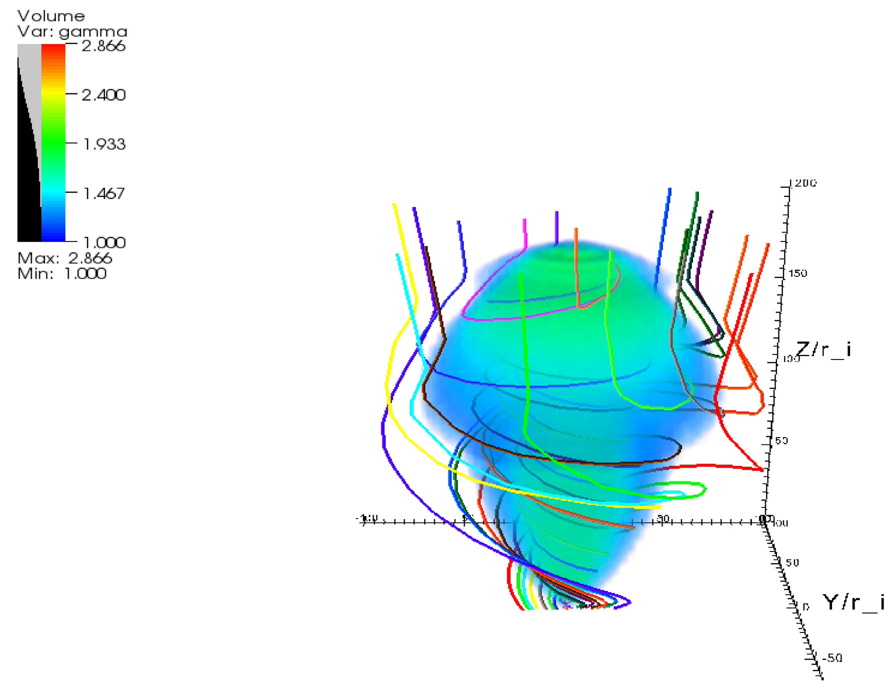
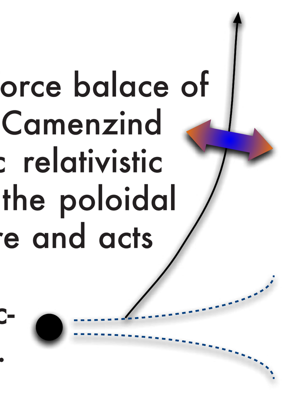


Figure 3:
Axisymmetric rendering of jet bulk Lorentz-factor Γ with helical field-lines after 18 inner disk-rotations.

Trans-field Force balance



Jet collimation is investigated in terms ot the trans-field force balace of the stationary flow. Chiueh et al. 1991[1] and Appl & Camenzind 1993[2] have first derived expressions for axisymmetric relativistic MHD-flows. When passing the critical Alfvén surface, the poloidal magnetic pressure force changes its decollimating nature and acts inwards.
Our simulations show that beyond the light-surface electric forces have a dominating decollimating contribution.

Force-balance equation perpendicular to field-line:

$$\overbrace{\kappa B_p^2\left(1 - M^2 - R^2\Omega_F^2\right)}^{F_{curv}} = \overbrace{\left(1 - R^2\Omega_F^2\right)\nabla_\perp \frac{B_p^2}{2}}^{F_{pbp}} + \nabla_\perp \left(\overbrace{\frac{B_\phi^2}{2}}^{F_{pbphi}} + \overbrace{P}^{F_{pp}}\right)$$

$$+ \left(\underbrace{\frac{B_\phi^2}{R}}_{F_{bphi}} - \underbrace{\frac{\rho h u_\phi^2}{R}}_{F_{cf}}\right)\nabla_\perp R - \underbrace{B_p^2 \Omega_F \nabla_\perp \left(R^2\Omega_F\right)}_{F_{el}} + \underbrace{\rho \nabla_\perp(\phi)}_{F_{grav}}$$

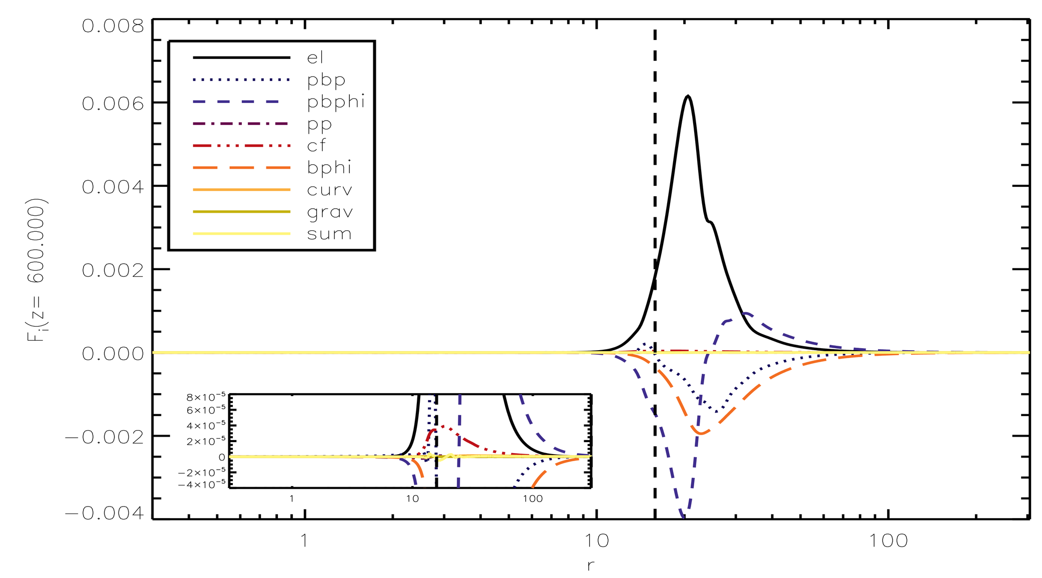


Figure 4:
Global force-balance on horizontal cut (at z=600 r_S) and 100x magnified inlay. Dashed vertical line represents the light-cylinder crossing where electric forces start to dominate. The terms are defined in the text.

1 Chiueh, T., Li, Z.-Y., & Begelman, M. C. 1991, ApJ, 377, 462
2 Appl, S. & Camenzind, M. 1993, A&A, 270, 71

Conversion of Poynting-Flux

We believe that relativistic jets are accelerated by magnetic torques, converting electromagnetic Poynting-flux into bulk kinetic motion. The efficiency of this process is quantified by the magnetisation parameter σ :

$$\sigma := \frac{\mathcal{F}_{em}}{\mathcal{F}_{kin}} = \frac{-\Omega_F R B_p B_\phi}{\Gamma^2 \rho h v_p}$$

the ratio of electromagnetic to mass energy flux expressed for axisymmetric flows. Ω_F denotes the angular velocity of the field-line being conserved in a stationary state. Another conserved quantity is the total energy flux to the rest-mass energy flux ratio μ:

$$\mu := \frac{\mathcal{F}_{em} + \mathcal{F}_{kin}}{\mathcal{F}_m} = const.$$

Alone from these considerations we see that the maximal Lorentz-factor Γ_{max} becomes:

$$\mu = \Gamma(\sigma + 1) \quad \Rightarrow \quad \Gamma_{max} = \mu.$$

As acceleration can only take place before the flow is cylindrical and is effective only for subfast flows (poloidal velocity below the fast magnetosonic wave-speed) this limiting value is typically not reached for self-collimating flows.

We systematically study the efficiency of acceleration in dependence on the injected Poynting flux and on magnetic field topology. Figure 5 shows the discussed quantities along a field-line. As we see, energy-conversion is efficient.

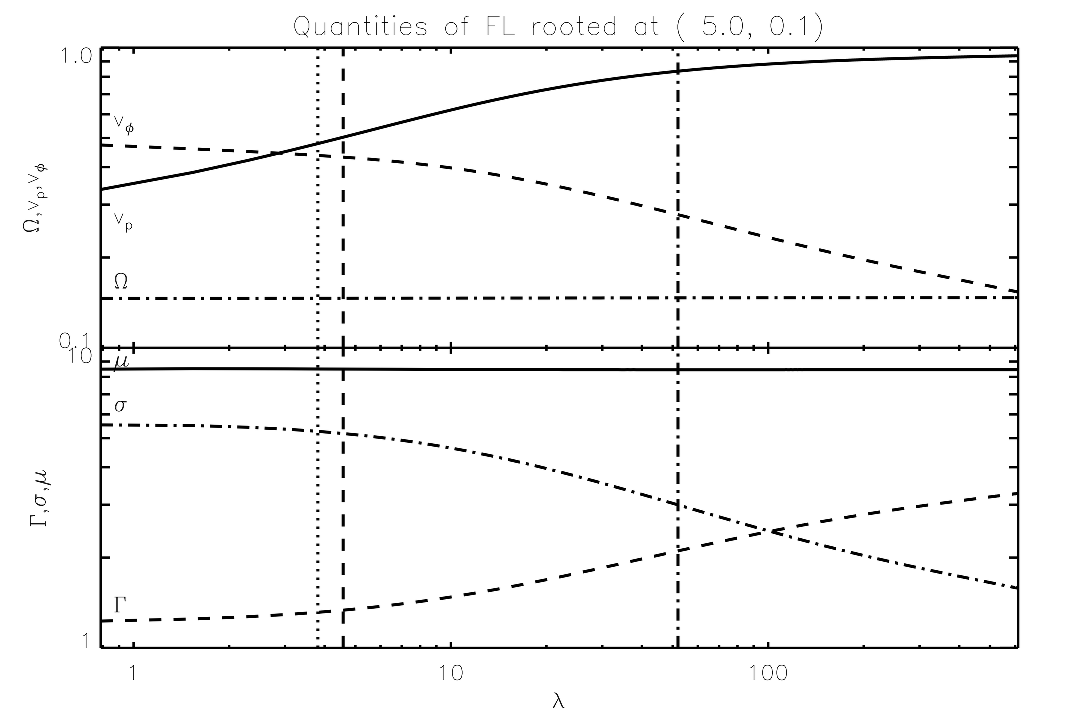


Figure 5:
Various quantities as a function of the distance on the field-line for the fiducial model. Top: Field-line velocity Ω, poloidal and toroidal velocity. Bottom: Lorentz-factor Γ, conversion efficiency σ and limiting function μ . Vertical lines are from left to right: Alfvén surface crossing, Light-cylinder crossing and fast-magnetosonic crossing.

Conclusions

We investigate the production of relativistic jets launched as disk-winds around circum- black hole disks. Collimation is an ubiquitous feature despite of electric forces.
For the simulation showed on this poster, energy conversion is effective, producing an asymptotic jet in equipartition in kinetic and electromagnetic energy. In general a higher Poynting-flux injection produces faster jets though the efficiency decreases.

Ask me, I am around:

Contact me:

Oliver Porth
Max-Planck-Institut für Astronomie
Königstuhl 17
D-69117 Heidelberg

porth@mpia.de
Phone: (+49) 6221 528-315