Κέντρο Ερευνών Αστρονομίας
και Εφαρμοσμένων Μαθηματικών
της Ακαδημίας Αθηνών

ΑΚΑΔΗΜΙΑ ΑΘΗΝΩΝ

Electric currents along astrophysical jets

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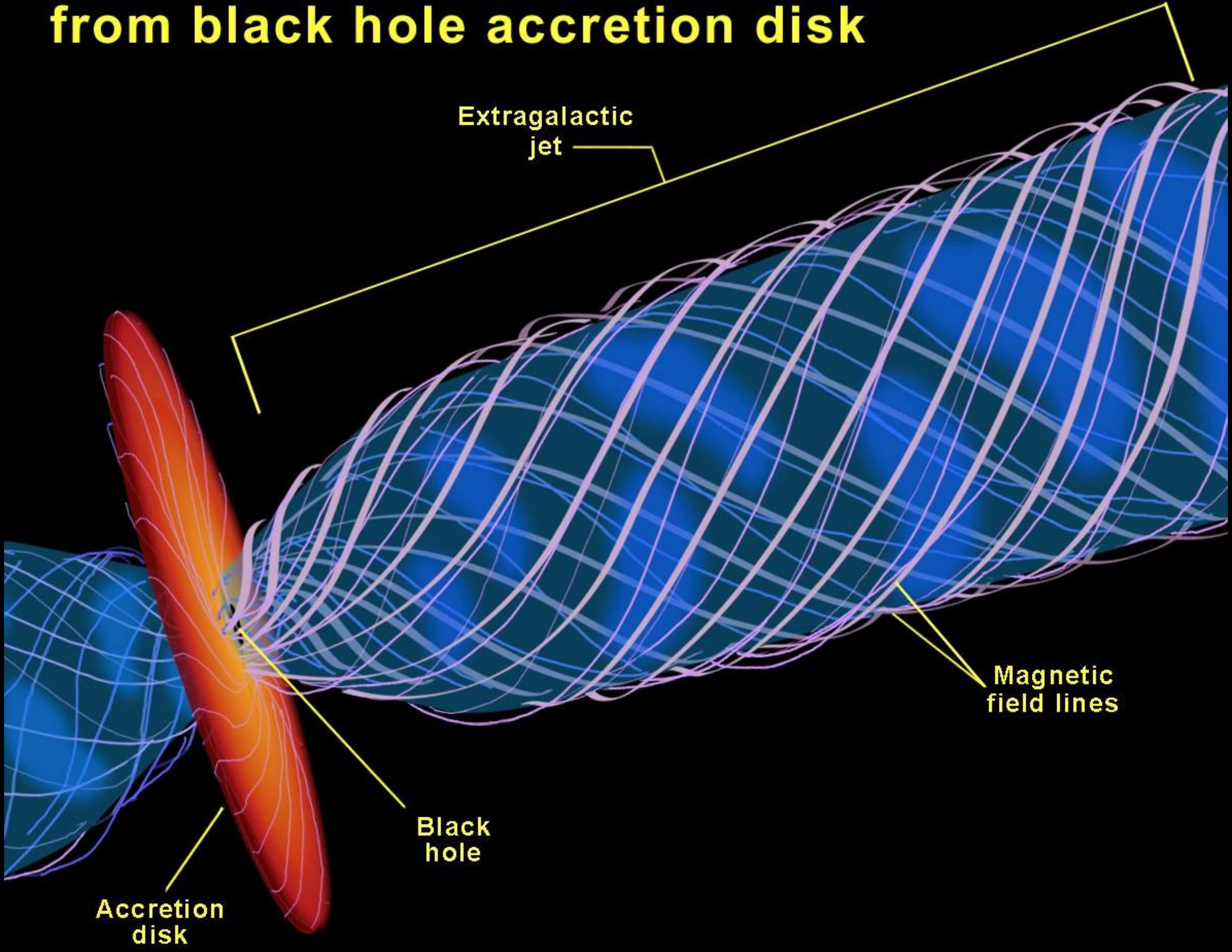
National Research Nuclear University MEPhI

Formation of extragalactic jets from black hole accretion disk



Large scale magnetic fields along astrophysical jets

Do they exist?

Can we observe them?

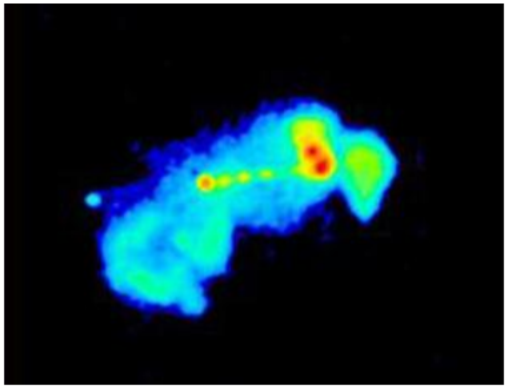
Electric currents along astrophysical jets

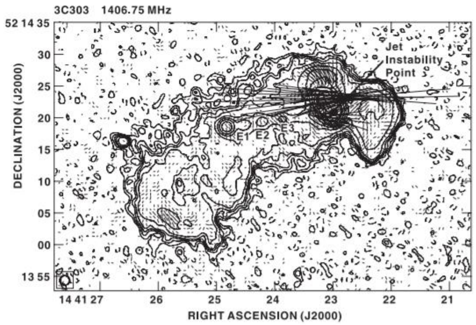
Can we observe them?

New Scientist

IN BRIEF 15 June 2011

Universe's highest electric current found

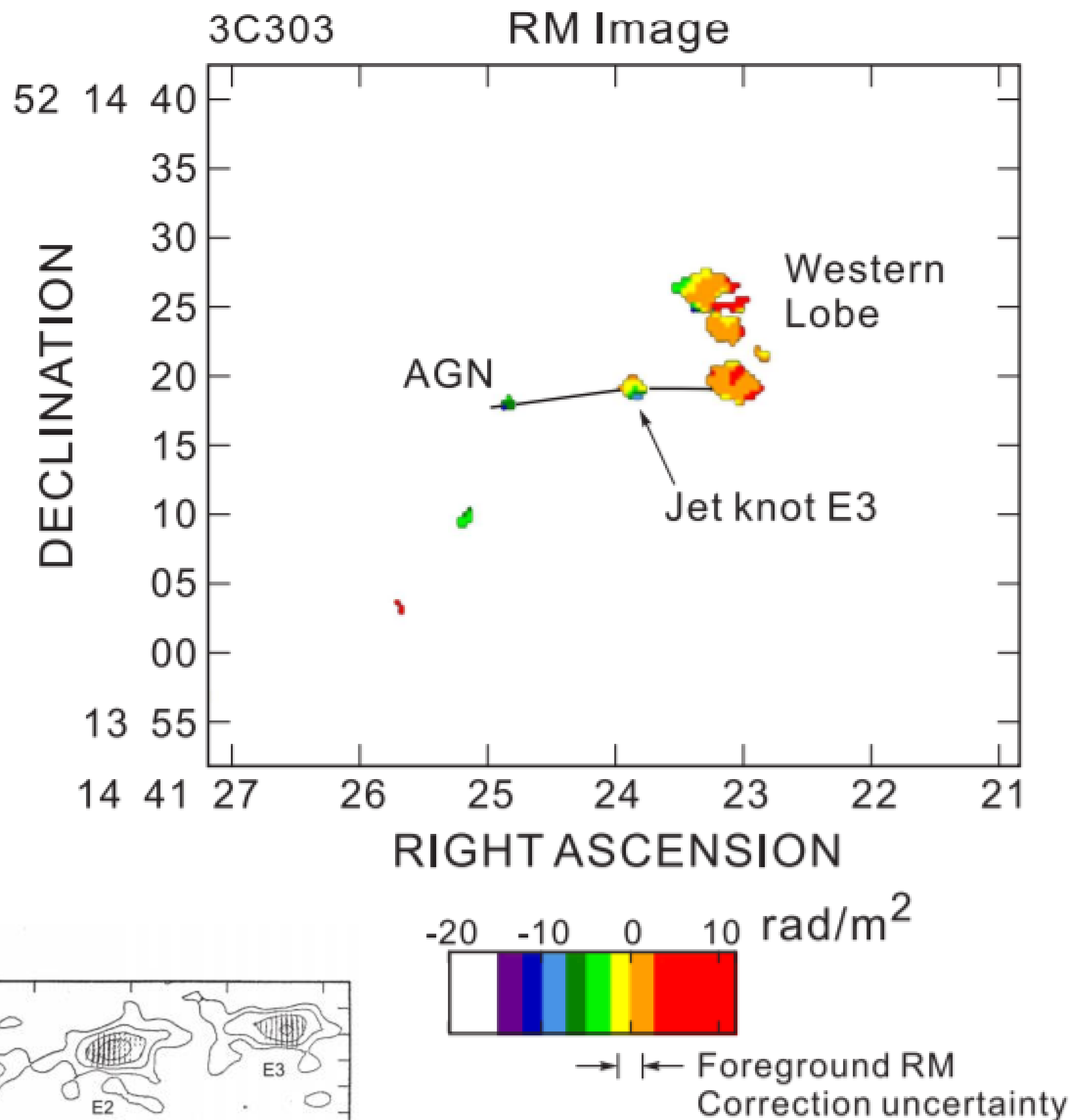


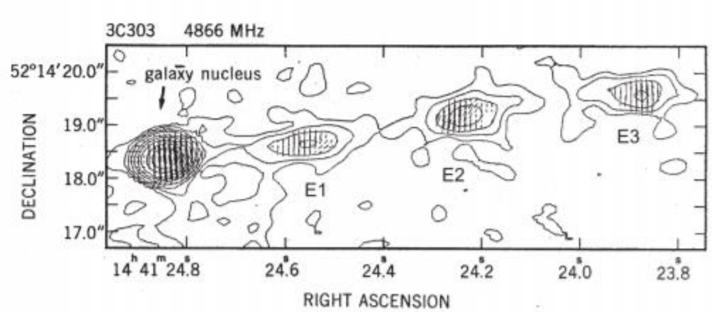


A COSMIC jet 2 billion light years away is carrying the highest electric current ever seen: 10^{18} amps, equivalent to a trillion bolts of lightning.

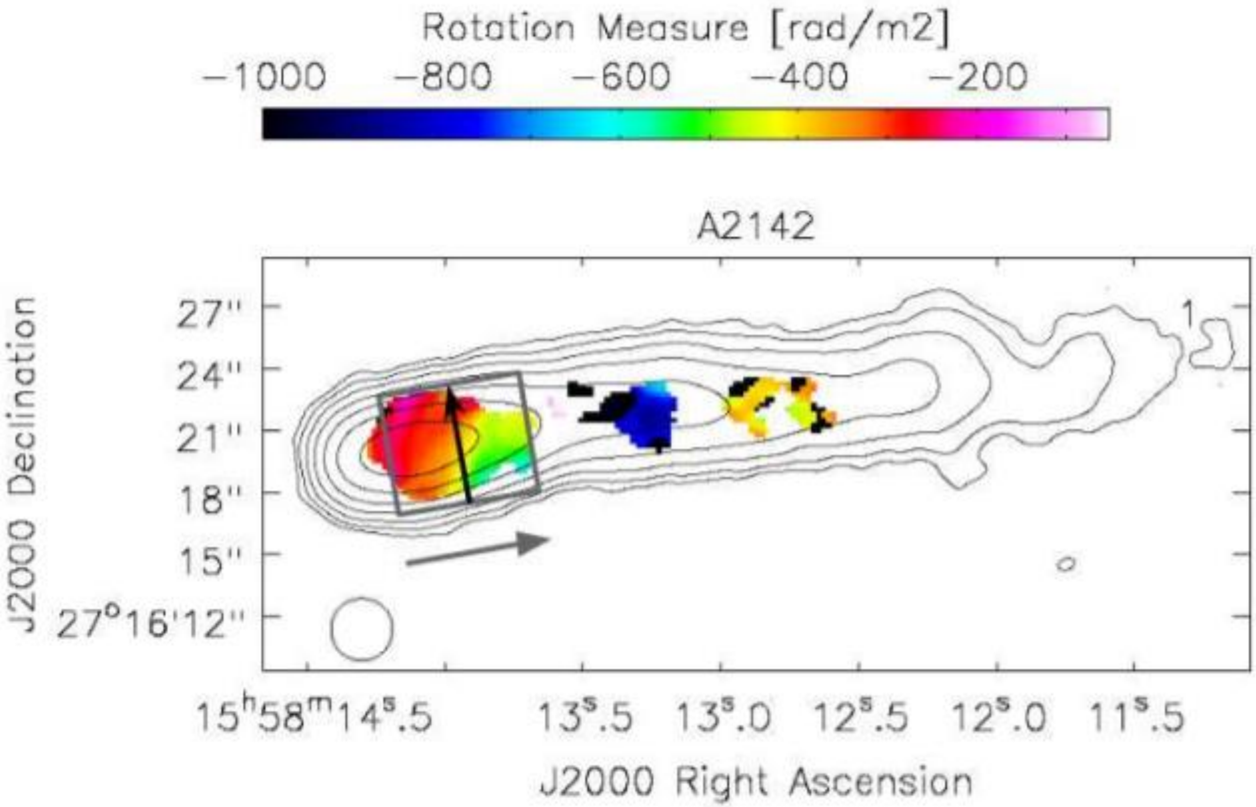
Philipp Kronberg of the University of Toronto in Canada and colleagues measured the alignment of radio waves around a galaxy called 3C303, which has a giant jet of matter shooting from its core. They saw a sudden change in the waves' alignment coinciding with the jet. "This is an unambiguous signature of a current," says Kronberg.

The team thinks magnetic fields from a colossal black hole at the galaxy's core are generating the current, which is powerful enough to light up the jet and drive it through interstellar gases out to a distance of about 150,000 light years (arxiv.org/abs/1106.1397).

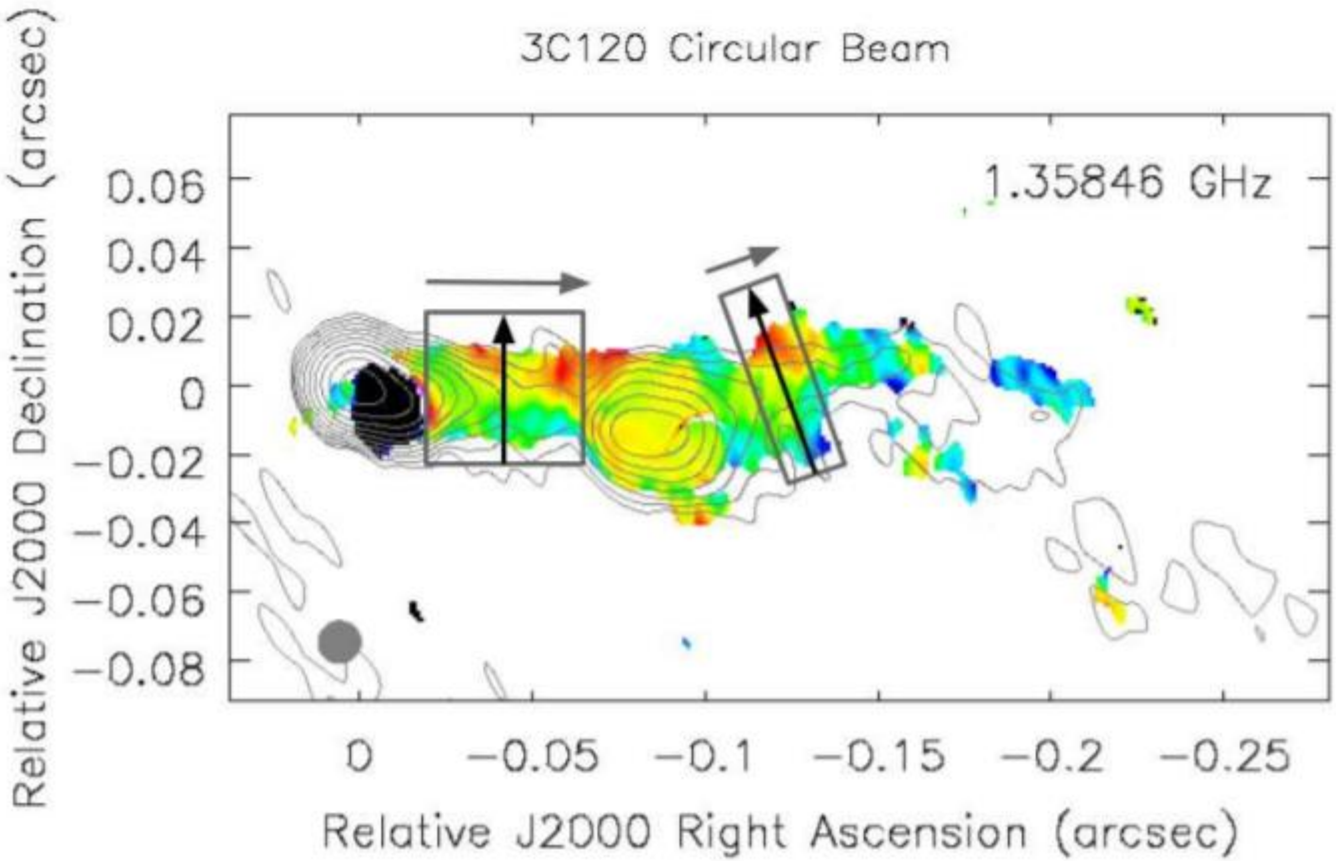




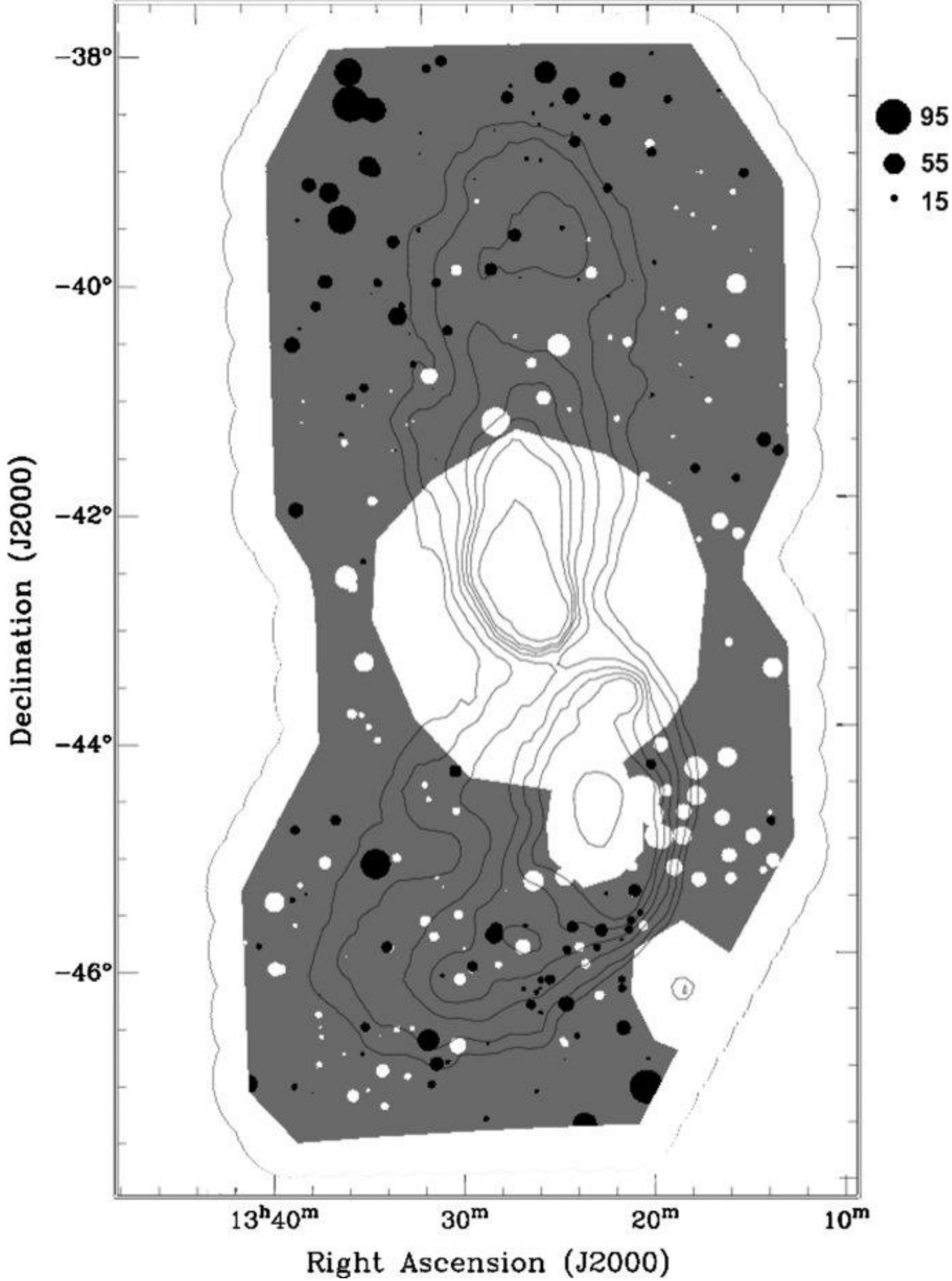
Kronberg, Lovelace, Lapenta, Colgate, ApJL 2011



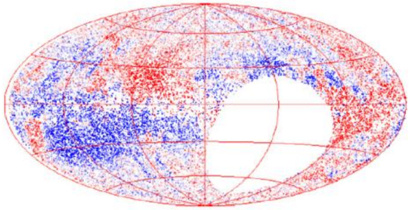
Gabuzda and collaborators; Govoni et al. A&A

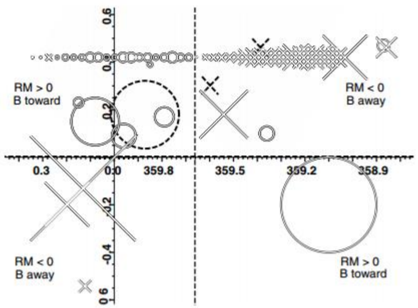


Christodoulou et al. A&A 2016



Feain et al. ApJ 2009





Law et al. ApJ 2011

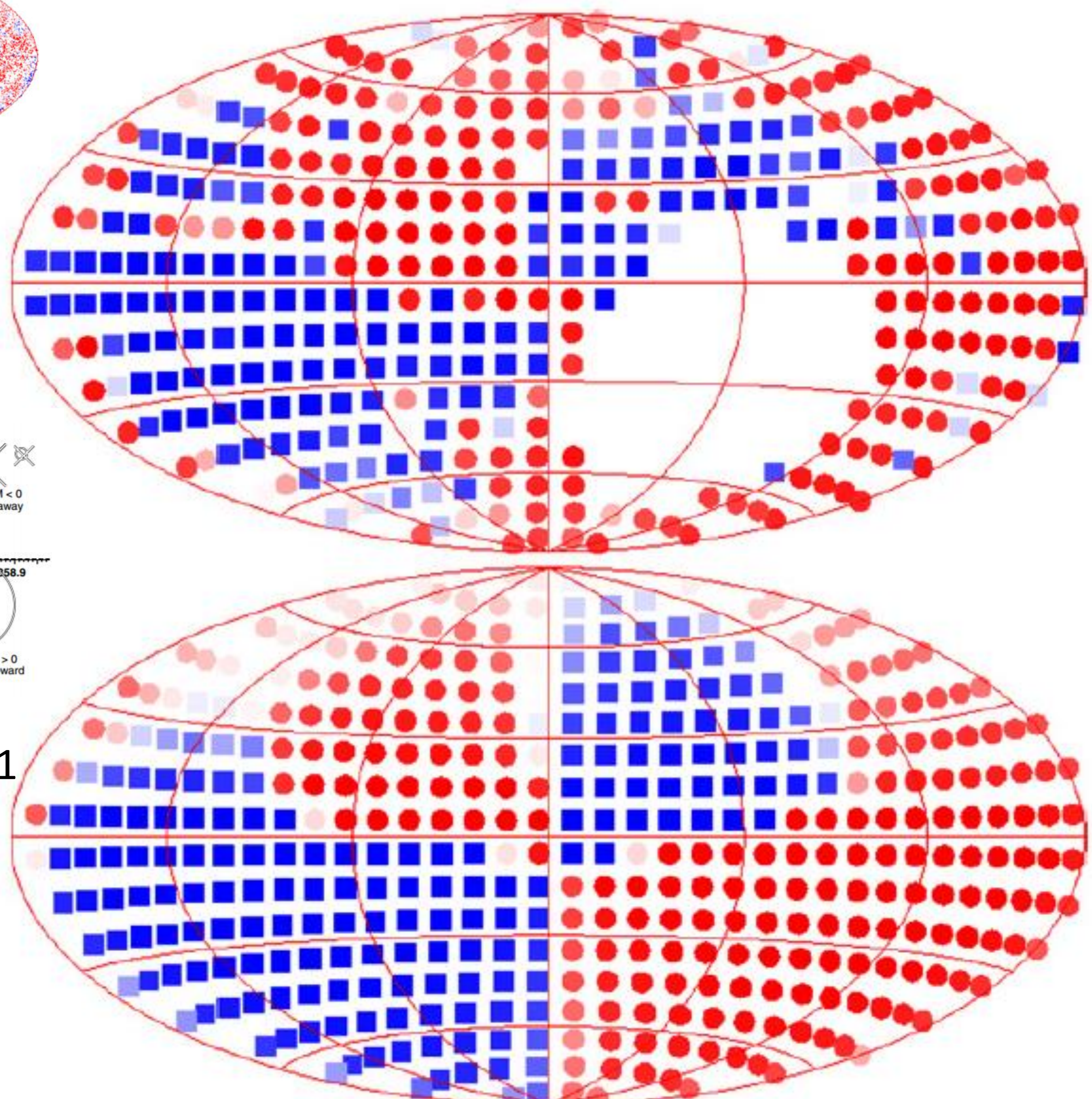


Figure 8. Average RMs in bins. Red circles (blue squares) represent positive (negative) RMs. The color intensity reflects the absolute magnitude. Top: NVSS data. Bottom: best-fit model.

37,543 VLA sources, Pshirkov et al. ApJ 2011

Christodoulou et al. 2015: Outflowing Electric Currents in Extragalactic Jets

Table 1. Transverse RM gradients on decaparsec to kiloparsec scales

No. (1)	Object name (2)	z (3)	RM gradient direction (4)	Projected distance from core (pc) (5)	Instrument and frequencies (6)	References[†] (7)
			Firm Gradients, Significances $\geq 3\sigma$			
1	0716+714	0.127	CCW*	3–35	VLBA, 4.6-15 GHz 1.4-1.7 GHz	**Mahmud et al. (2013)** Healy (2013)
2	0923+392	0.695	CCW*	20	VLBA, 4.6-15 GHz	**Gabuzda et al. (2014b)**
3	5C4.114 (N)	$> 0.023^a$	CCW	> 2000	VLA, 1.4-4.9 GHz	Bonafede et al. (2010); **Gabuzda et al. (2015b)**
4	5C4.114 (S)	$> 0.023^a$	CCW	> 1500	VLA, 1.4-4.9 GHz	Bonafede et al. (2010); **Gabuzda et al. (2015b)**
5	A2142A	0.091	CCW	to $\simeq 10,000$	VLA, 4.5-8.5 GHz	Govoni et al. (2010); **this paper**
6	1652+398	0.034	CCW	20	VLBA, 8.4-1.7 GHz	**Croke et al. (2010)**
7	1749+701	0.77	CCW*	75–100	VLBA, 1.4-1.7 GHz	**Mahmud et al. (2013)**
8	3C380	0.692	CCW	70–210	VLBA, 1.4-5.0 GHz	**Gabuzda et al. (2014a)**
9	2037+511	1.687	CCW*	40	VLBA, 4.6-15 GHz	**Gabuzda et al. (2014b)**
			Tentative Gradients			
1	0156−252	2.09	CCW	4000	VLA, 1.4-8.5 GHz	Athreya et al. (1998)
2	3C120	0.033	CCW	25–80	VLBA, 1.4-1.7 GHz	Coughlan et al. (2010); this paper
3	M87	0.004	CCW	60, 960, 1400	VLA, 8-43 GHz	Algaba et al. (2013)
4	5C4.152	$\ldots^a$	CCW	15″	VLA, 4.5-8.3 GHz	Bonafede et al. (2010); this paper
5	Cen A	0.0018	CCW	130,000	ATCA, 1.3-1.5 MHz	Feain et al. (2009); this paper
6	3C303	0.141	CCW	20,000	VLA, 1.4-8.5 GHz	Kronberg et al. (2011)
7	3C465	0.0313	CCW	40,000–100,000	VLA, 4.5-8.9 GHz	Eilek & Owen (2002)

[†] References in bold indicate papers that present quantitative analyses of the statistical significance of the corresponding RM gradients.
*RM gradients in the CW direction are present closer to the jet base.
[a] Exact redshift not available.

Christodoulou et al. A&A 2016

Out of 87 kpc jets only 16 with RM gradients

Christodoulou et al. 2015: Outflowing Electric Currents in Extragalactic Jets

Table 1. Transverse RM gradients on decaparsec to kiloparsec scales

No. (1)	Object [illegible]ame (2)	*z* (3)	RM gradi[illegible] [illegible] (4)	Proj[illegible]ed [illegible]tance fro[illegible] (pc) (5)	[illegible]nstrument a[illegible] f[illegible]que[illegible] (6)	References† (7)
			Fi[illegible] Gr[illegible]ents [illegible]ignificance [illegible]			
1	0716+714	0.127	CCW*	3–35	VLBA, 4.6-1[illegible] GHz; 1.4-1.7 G[illegible]	**Ma[illegible]mud et al. (2013)**; Healy (2013)
2	0923+392	0.695	CCW*	20	VLBA, 4.6-15 GHz	**Gabuzda et al. (2014b)**
3	5C4.114 (N)	> 0.023^a	CCW	> 2000	VLA, 1.4-4.9 GHz	Bonafede et al. (2010); **G[illegible]uzda et al. (2015b)**
4	5C4.114 (S)	> 0.023^a	C[illegible]W	> 1[illegible]	VLA, 1.4-4.9 GHz	B[illegible]afede et al. (2010); **G[illegible] et al. (2015b)**
5	A2142A	[illegible]09	C[illegible]W	to ≃ 10,0[illegible]	VLA, 4[illegible]8[illegible]	[illegible]ovo[illegible] et al. [illegible]2010); **this paper**
6	1652+39[illegible]	[illegible]03[illegible]	C[illegible]W	20	VLBA, 8[illegible]7[illegible]	**[illegible]rok[illegible] t al. (2010)**
7	1749+701	0.77	CCW*	75–100	VLBA, 1.4-1.7 GHz	**Mahmud et al. (2013)**
8	3C380	0.692	CCW	70–210	VLBA, 1.4-5.0 GHz	**Gabuzda et al. (2014a)**
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			Tentative Gradients			
1	0156−252	2.09	CCW	4000	VL[illegible] 1.[illegible]8.5 GHz	Athreya et al. (1998)
2	3C1[illegible]	0[illegible]	[illegible]W	25–80	VL[illegible] 1.4-1.7 GHz	Cough[illegible] et al. (2010); this paper
3	M8[illegible]	0[illegible]	[illegible]W	[illegible]9[illegible]0[illegible]	[illegible] 3 G[illegible]	[illegible]gab[illegible] (2013)
4	5C4.[illegible]	[illegible]^a	[illegible]W	[illegible]	VL[illegible] 4.[illegible]8.3[illegible]	B[illegible]af[illegible] et a[illegible]010); this paper
5	Cen[illegible]	0.[illegible]18	[illegible]W	13[illegible]00	AT[illegible] 1[illegible]1.[illegible]Hz	[illegible]ai[illegible] al. (20[illegible]); this paper
6	3C30[illegible]	0.141	CCW	20,000	VLA, 1.4-8.5 GHz	Kro[illegible]berg et al. (2011)
7	3C465	0.0313	CCW	[illegible],000–100,000	VLA, 4.5-8.9 GHz	Eilek & Owen (2002)

† References in bold indicate papers that present quantitative analyses of the statistical significance of the corresponding RM gradients.
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Electric currents: All outward!

Table 1. Transverse RM gradients on decaparsec to kiloparsec scales

No.	Object name	z	RM gradient direction	Projected distance from core (pc)	Instrument and frequencies	References[†]
(1)	(2)	(3)	(4)	(5)	(6)	(7)
			Firm Gradients, Significances $\geq 3\sigma$			
1	0716+714	0.127	CCW*	3–35	VLBA, 4.6-15 GHz	**Mahmud et al. (2013)**
					1.4-1.7 GHz	Healy (2013)
2	0[illegible]3+392	0.695	CCW*	20	VLBA, 4.6-15 GHz	**Gabuzda e[illegible]l. (2014b)**
3	5C[illegible]114[illegible]	> [illegible]	CC[illegible]	[illegible]000	VL[illegible] 1.[illegible]G[illegible]	[illegible]de[illegible](2[illegible]
						[illegible]bu[illegible]a e[illegible]l. (2[illegible]5b)
4	5C[illegible]1[illegible](S)	> [illegible]023[a]	CC[illegible]	> 1500	VL[illegible] 1.[illegible]4.9 G[illegible]z	[illegible]na[illegible]e e[illegible]l. (2010
						[illegible]bu[illegible]a et[illegible](2[illegible])
5	A2142A	0.091	CCW	to ≃ 10, 000	VLA, 4.5-8.5 GHz	Govoni et al. (2010); **this paper**
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8	3C380	0.692	CCW	70–210	VLBA, 1.4-5.0 GHz	**Gabuzda et al. (2014a)**
9	2037+511	[illegible]1.687	CCW*	40	VLBA, 4.6-15 GHz	**G[illegible]uzd[illegible]t al. (2014b)**
			T[illegible]a[illegible]a[illegible]ents			
1	0156–252	[illegible]09	CCW	[illegible]000	[illegible]-8.5 GH	[illegible]hrey[illegible]et al. (1998)
2	3C120	[illegible]33	CCW	[illegible]–80	[illegible]4-[illegible]G	[illegible]ugh[illegible] et a[illegible] (2010); this paper
3	M87	0.[illegible]04	CCW	60, [illegible]0	VL[illegible] 8-4[illegible]	[illegible]gab[illegible]t al. (2013)
4	5C4.152	…[a]	CCW	15″	VLA, 4.5-8.3 GHz	Bonafede et al. (2010); this paper
5	Cen A	0.0018	CCW	130,000	ATCA, 1.3-1.5 MHz	Feain et al. (2009); this paper
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Large scale magnetic fields along astrophysical jets

Do they exist? Yes!

Where do they come from?

The Cosmic Battery

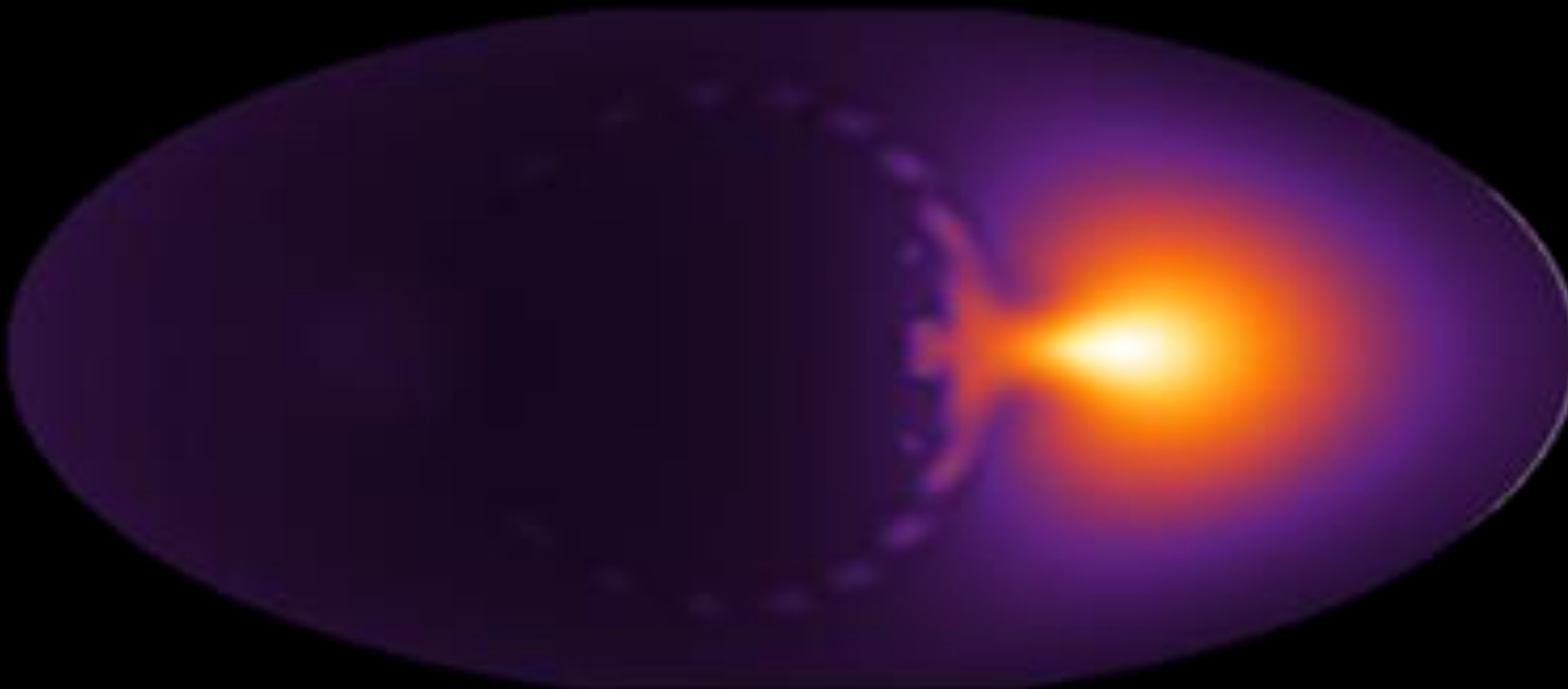
Contopoulos & Kazanas 1998

Contopoulos et al. 2006, 09, 15

Christodoulou et al. 2008, 16

Kylafis et al. 2012

Gabuzda et al. 2012



Koutsantoniou & Contopoulos ApJ 2014, 17

MNRAS 000, 000–000 (0000) Preprint 30 May 2017 Compiled using MNRAS LATEX style file v3.0

Numerical simulations of the Cosmic Battery in accretion flows around astrophysical black holes

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[2] National Research Nuclear University (MEPhI), Moscow 115409, Russia
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[4] Humboldt Fellow
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[6] Einstein Fellow
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[8] Astrophysics Science Division, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA
[9] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA

30 May 2017

The conservation laws for gas density, energy and momentum, radiation energy and momentum, and photon number can be written in covariant form,

$$(\rho u^\mu)_{;\mu} = 0, \tag{7}$$

$$(T^\mu{}_\nu)_{;\mu} = G_\nu, \tag{8}$$

$$(R^\mu{}_\nu)_{;\mu} = -G_\nu, \tag{9}$$

$$(nu^\mu)_{;\mu} = \dot{n}, \tag{10}$$

where ρ is the gas density in the comoving fluid frame, u^μ is the gas four-velocity, T^μ_ν is the MHD stress-energy tensor,

$$T^\mu{}_\nu = (\rho + u_{\rm int} + p + b^2)u^\mu u_\nu + (p + \frac{1}{2}b^2)\delta^\mu{}_\nu - b^\mu b_\nu, \tag{11}$$

with $u_{\rm int}$ and $p = (\gamma_{\rm int} - 1)u_{\rm int}$ representing the internal energy density and pressure of the gas in the comoving frame with adiabatic index, $\gamma_{\rm int}$, and b^μ - the magnetic field 4-vector (Gammie et al. 2003). R^μ_ν stands for the radiative stress-energy tensor and n for the photon number density.

where $h^\mu_\nu = \delta^\mu_\nu + u^\mu u_\nu$ is the projection tensor, and u^μ is the gas four-velocity. The new components of the dual electromagnetic field tensor, therefore, are

$$F^{*\mu\nu}_{\rm CB} = -\epsilon^{\mu\nu\alpha\beta}(E_{\rm CB})_\alpha u_\beta = -\epsilon^{\mu\nu\alpha\beta}h_{\alpha\gamma}G^\gamma u_\beta \frac{m_{\rm p}}{\rho e c} , \tag{18}$$

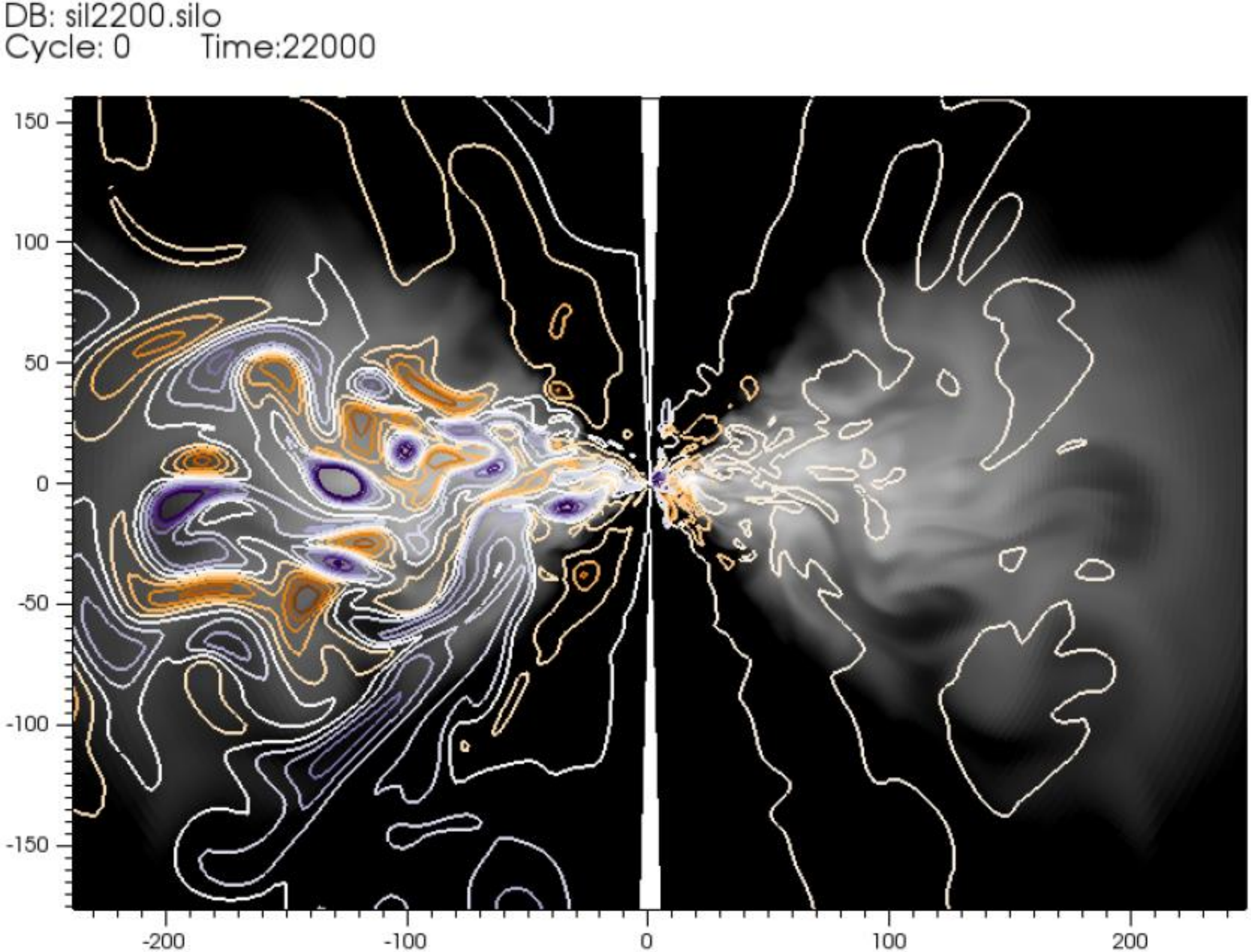
which leads to the modified induction equation

$$\partial_t(\sqrt{-g}B^i) = -\partial_j\left(\sqrt{-g}(b^j u^i - b^i u^j) + \sqrt{-g}\epsilon^{ij\alpha\beta}(E_{\rm CB})_\alpha u_\beta\right)$$

$$= -\partial_j\left(\sqrt{-g}(b^j u^i - b^i u^j + \epsilon^{ij\alpha\beta}h_{\alpha\gamma}G^\gamma u_\beta \frac{m_{\rm p}}{\rho e c})\right) . \tag{19}$$

It is interesting that the CB term involves the radiation four-force density G^μ which is already calculated in the numerical code, and does not require the calculation of extra quantitities. Therefore, its inclusion has no extra computational cost for an MHD+radiation simulation.

This is the first time that the extra CB term appears in the general relativistic form of the induction equation. Our goal in the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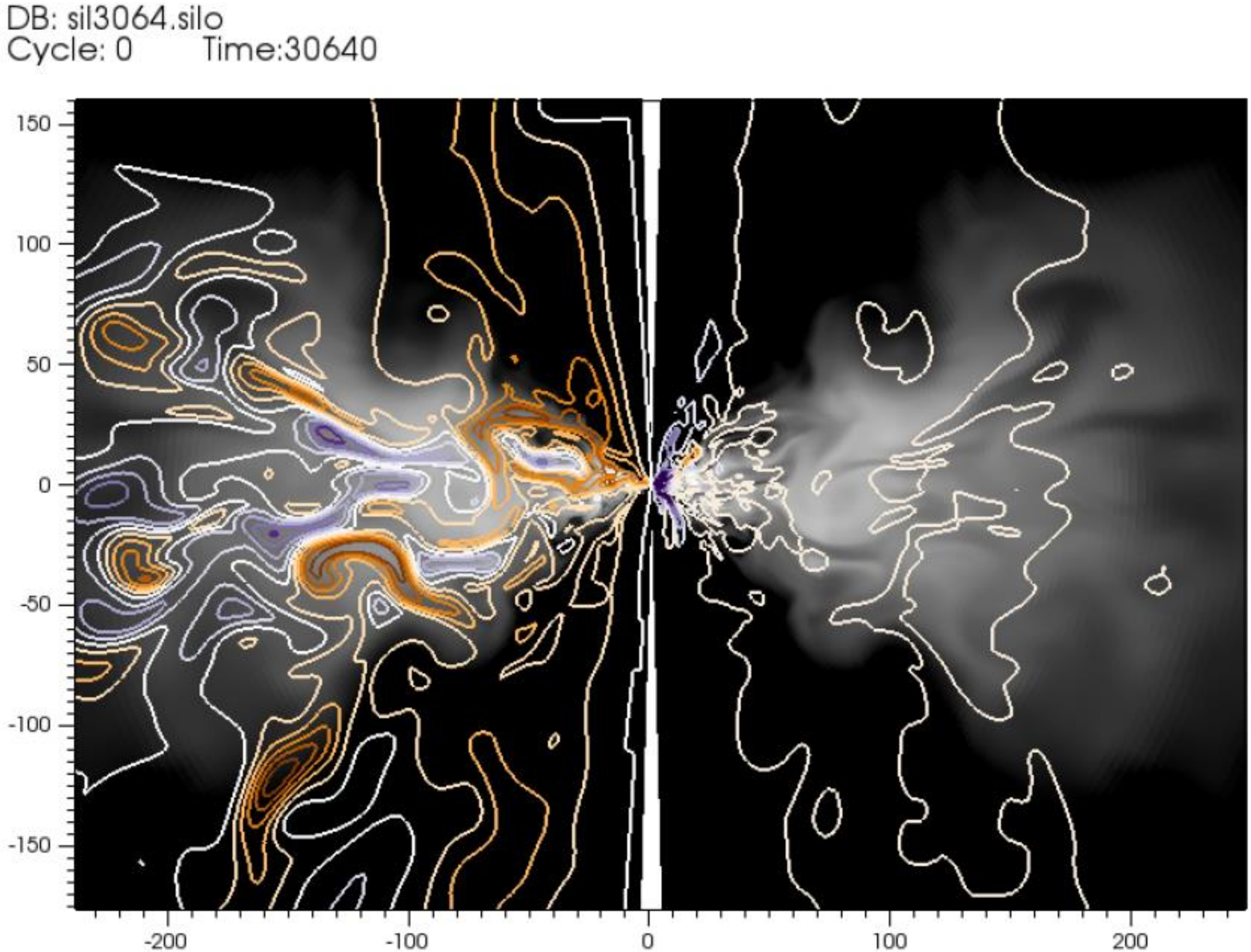
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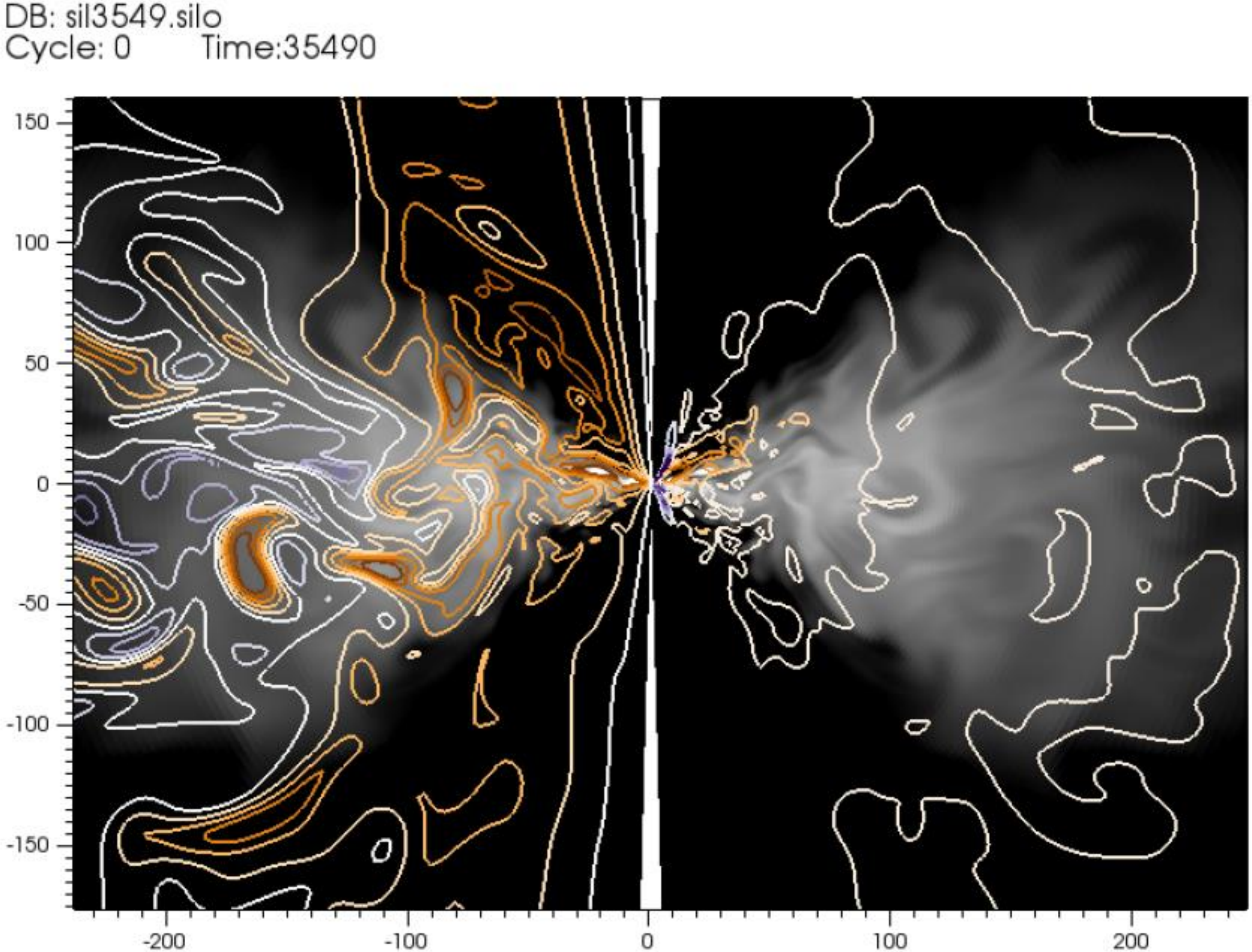
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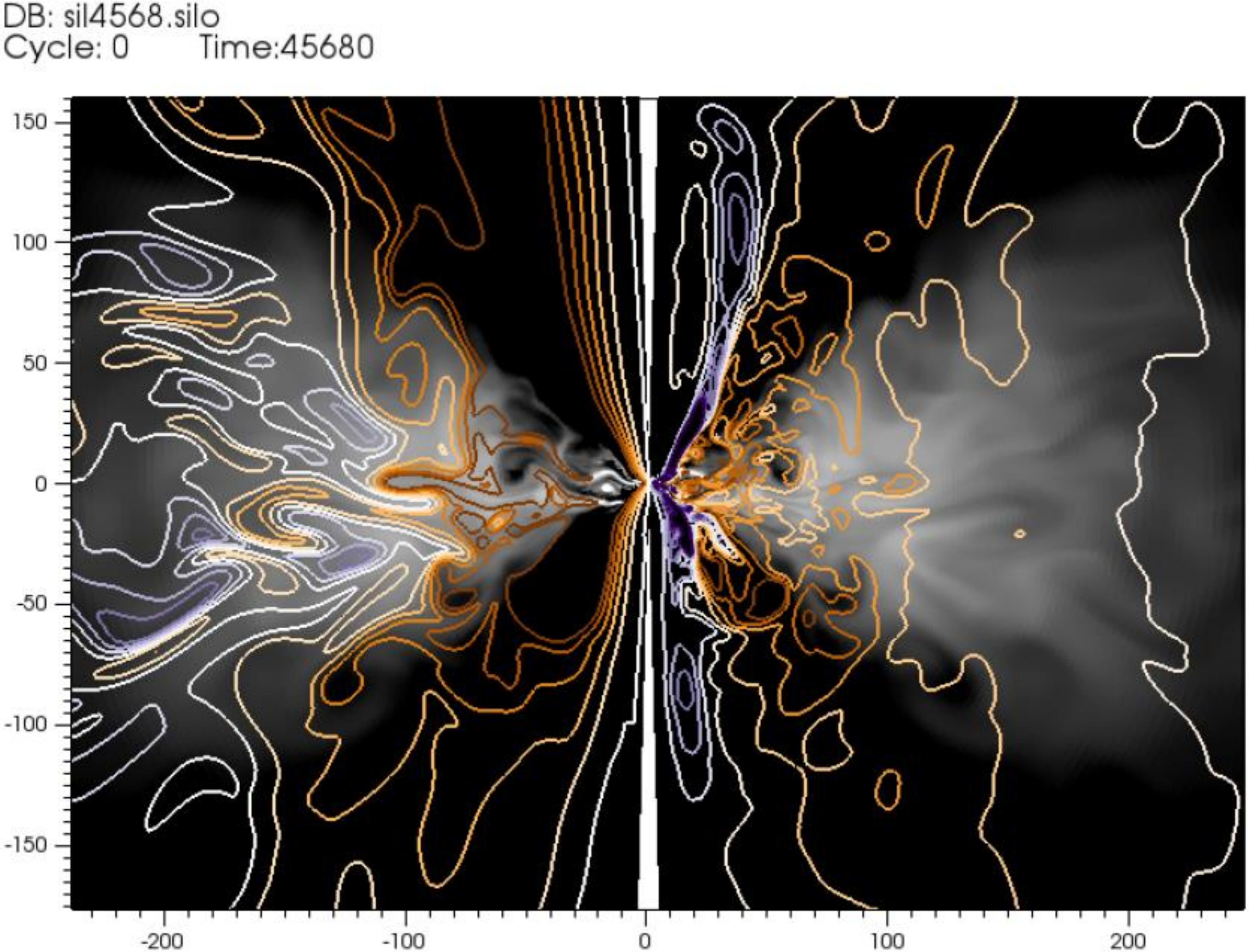
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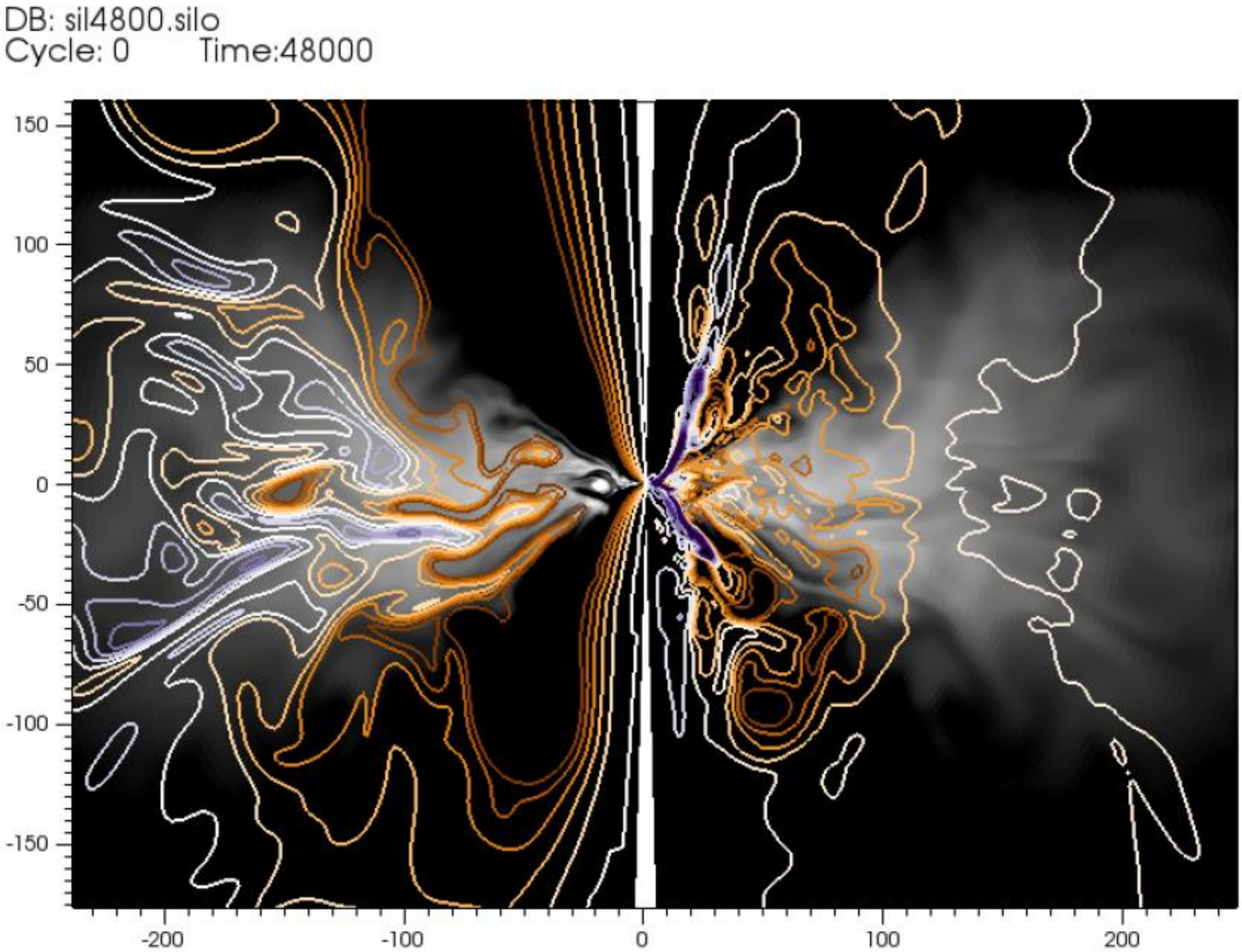
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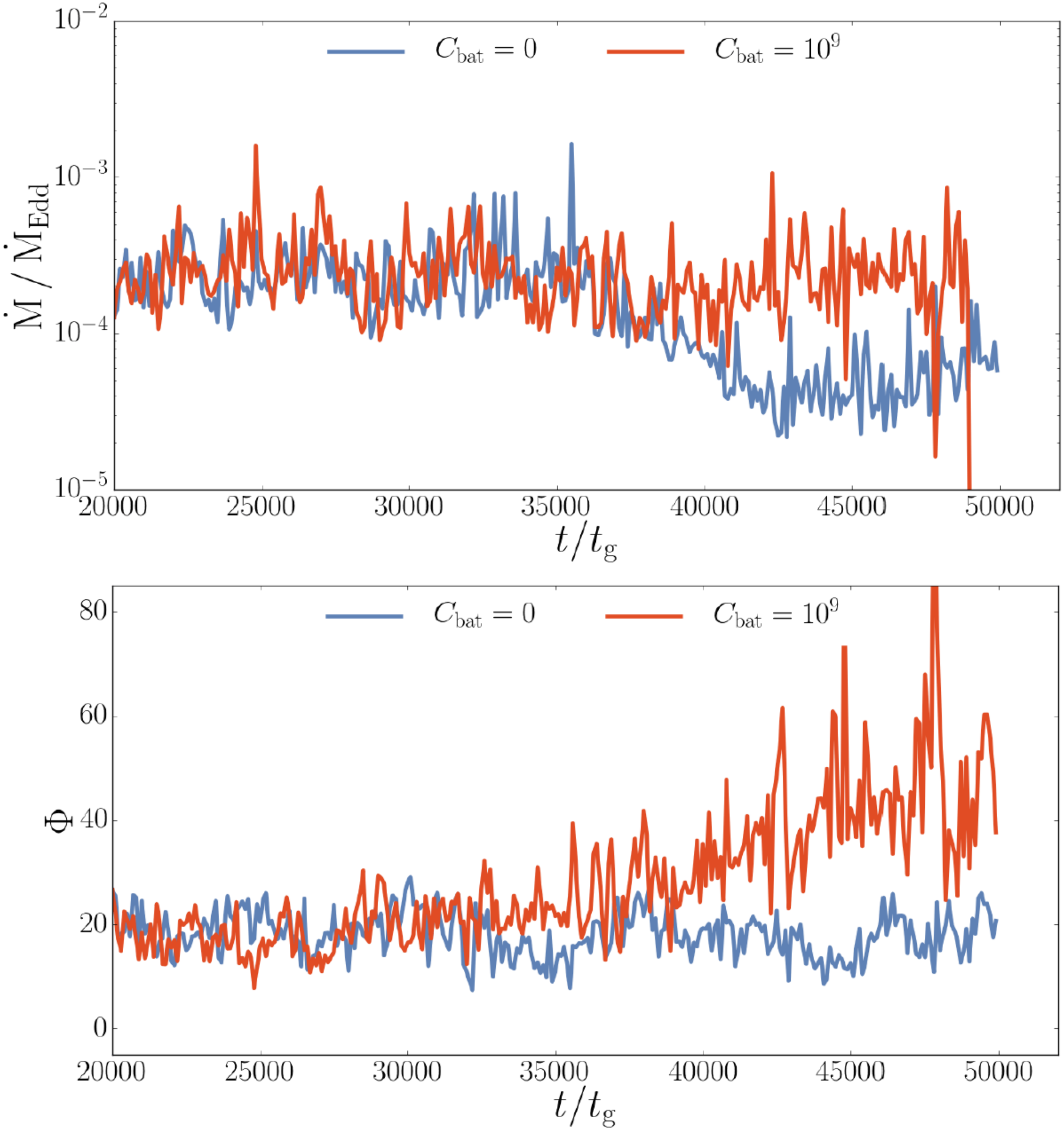
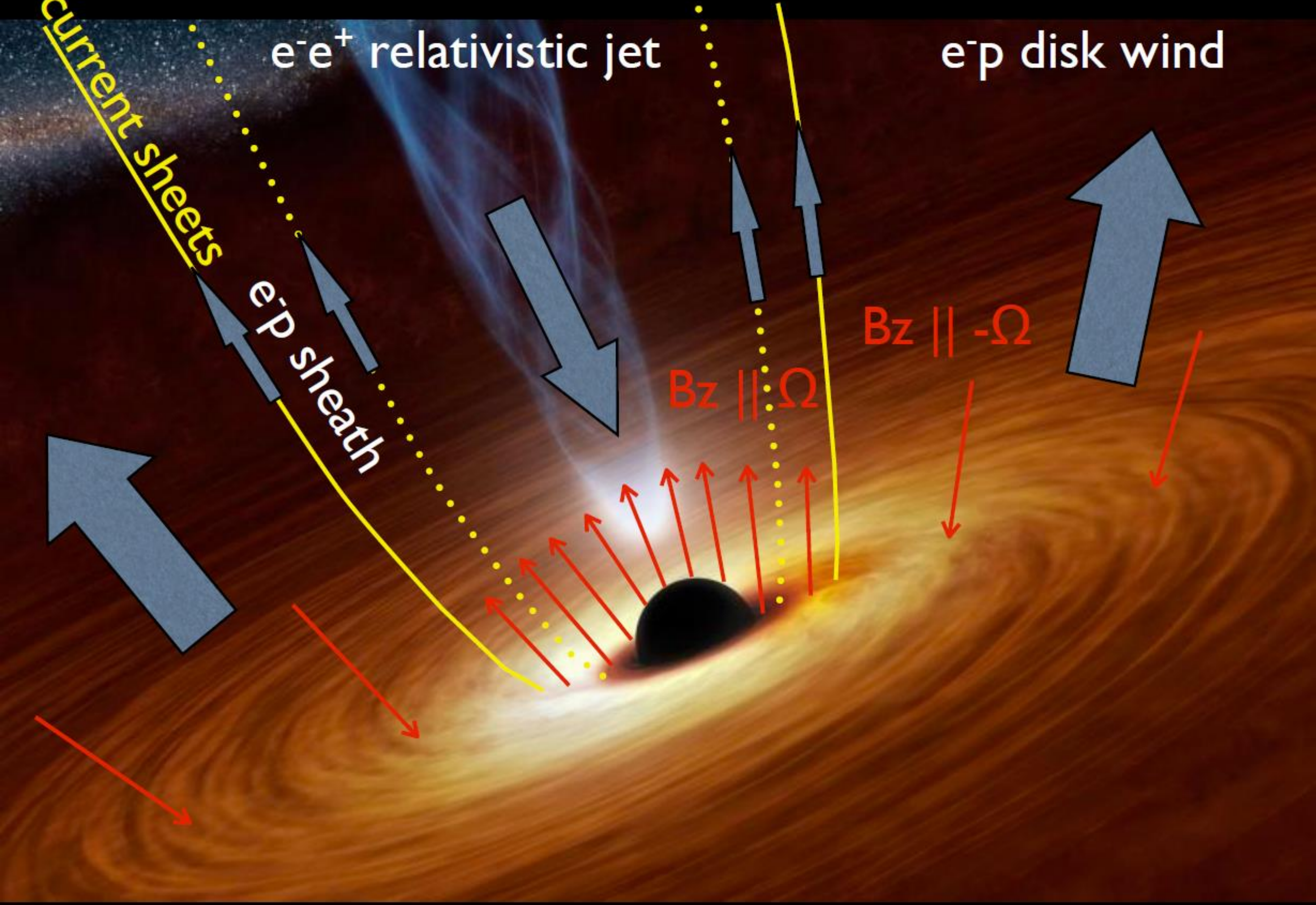
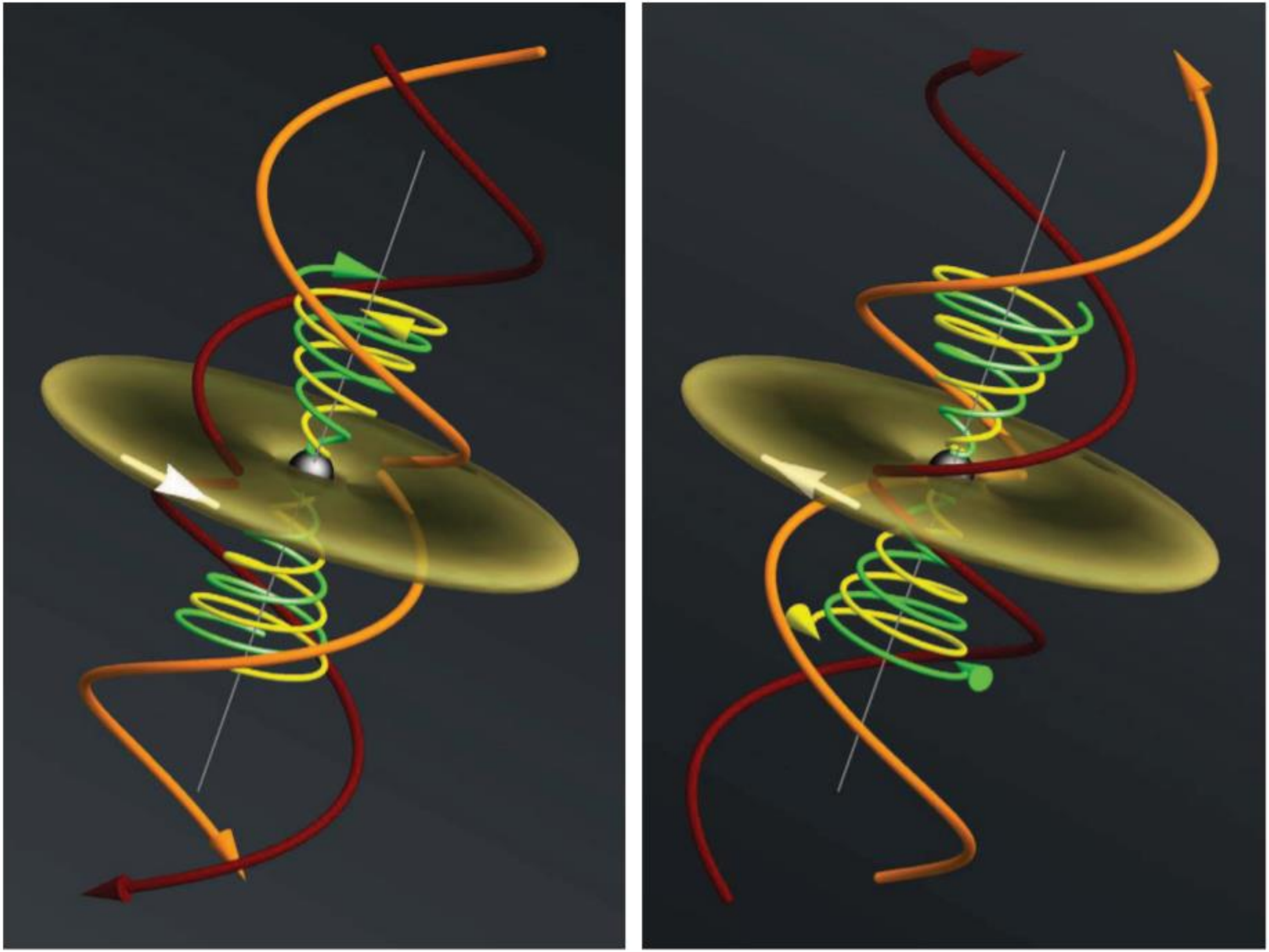

$C_{\rm bat}=0$
$C_{\rm bat}=10^9$
$\dot{M}\,/\,\dot{M}_{\rm Edd}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
20000
25000
30000
35000
40000
45000
50000
$t/t_{\rm g}$
$C_{\rm bat}=0$
$C_{\rm bat}=10^9$
Φ
80
60
40
20
0
20000
25000
30000
35000
40000
45000
50000
$t/t_{\rm g}$


e$^-$e$^+$ relativistic jet
e$^-$p disk wind
current sheets
e$^-$p sheath
Bz || Ω
Bz || -Ω



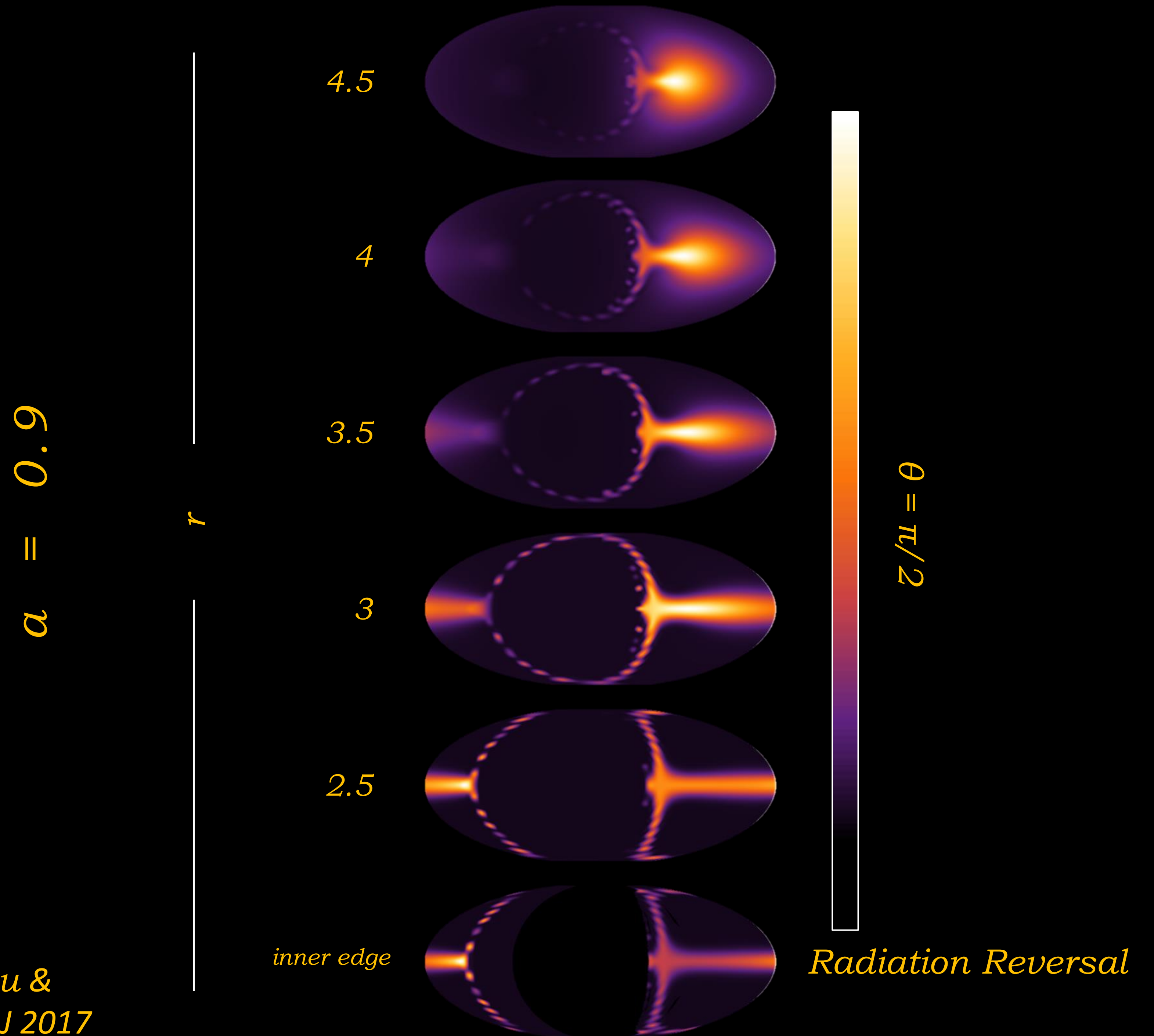
Electric currents along astrophysical jets

They exist and they are observable!

Always flowing outward on kpc scales!

Inner or outer?   Core or sheath?

How can we observe more of them?



Koutsantoniou & Contopoulos ApJ 2017