Cyclotron absorption lines in the era of Suzaku and NuSTAR

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- Energy spectrum
- Cyclotron absorption line
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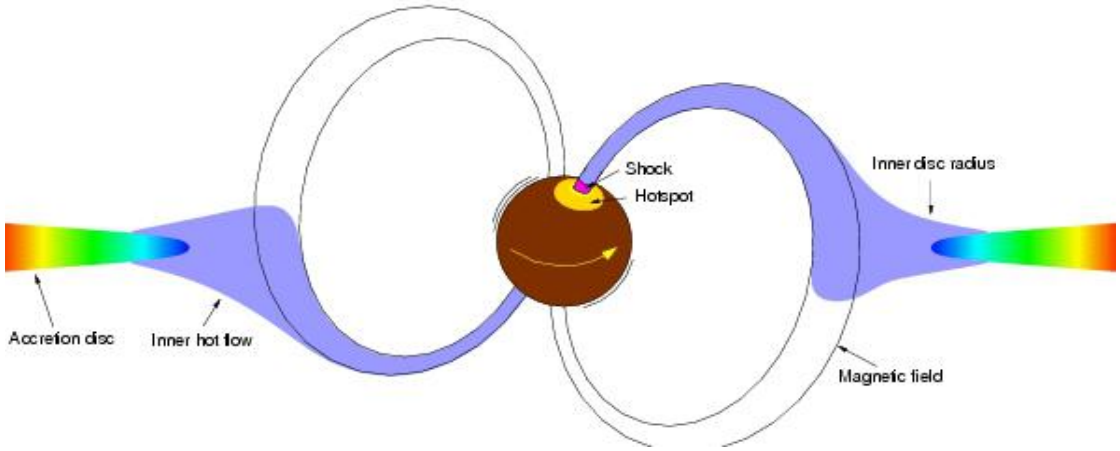
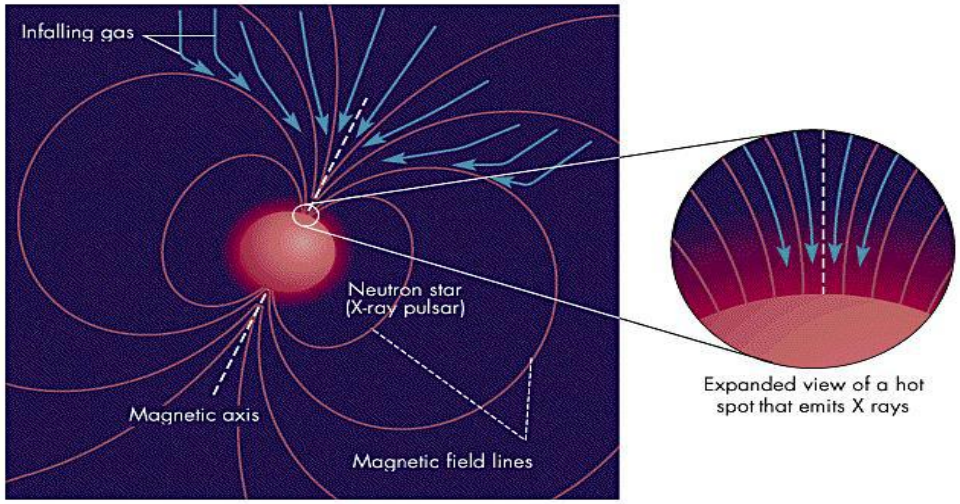
Accretion powered X-ray pulsar

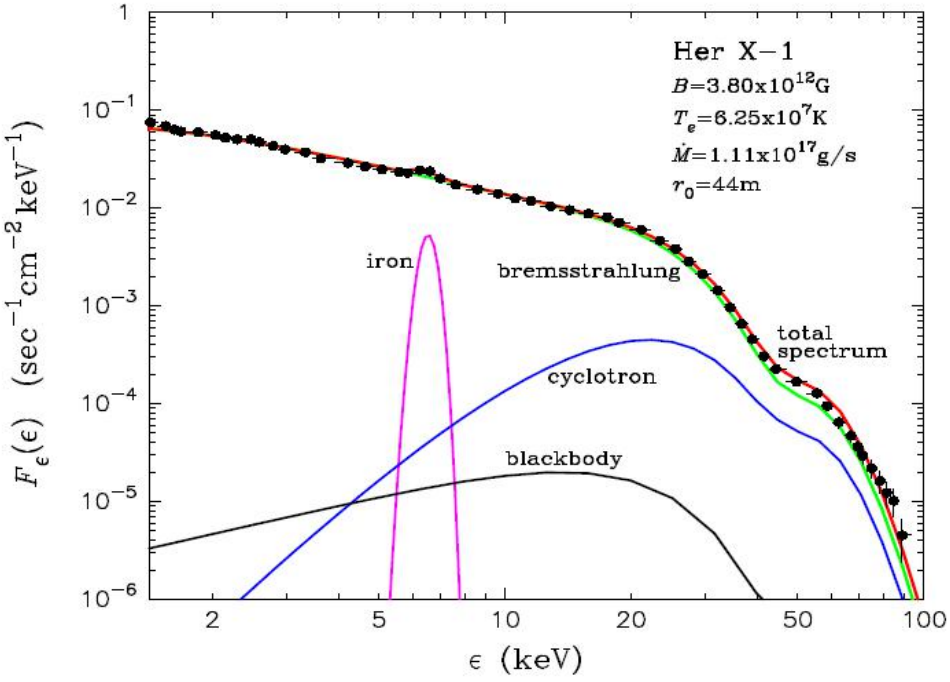
- Rotating neutron star.
- Strong magnetic field ~10^{12} G
- Flow couples to the magnetic field at Alfven radius.
- Chanelling of matter along the magnetic field lines
- Formation of accretion column
- Emission from polar cap region & pulsations





Continuum spectrum of X-ray pulsars

- Continuum Spectrum
- Line of sight absorption
- Soft excess
- Emission lines
- Cyclotron resonance scattering features

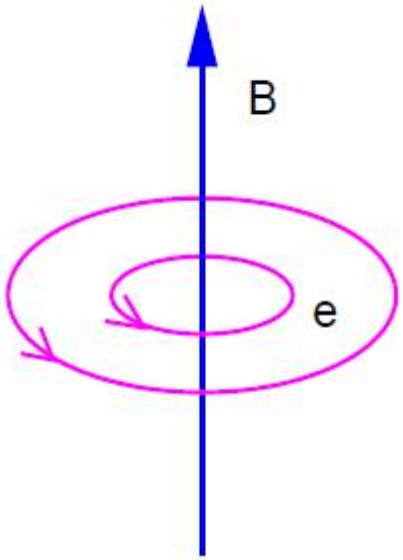


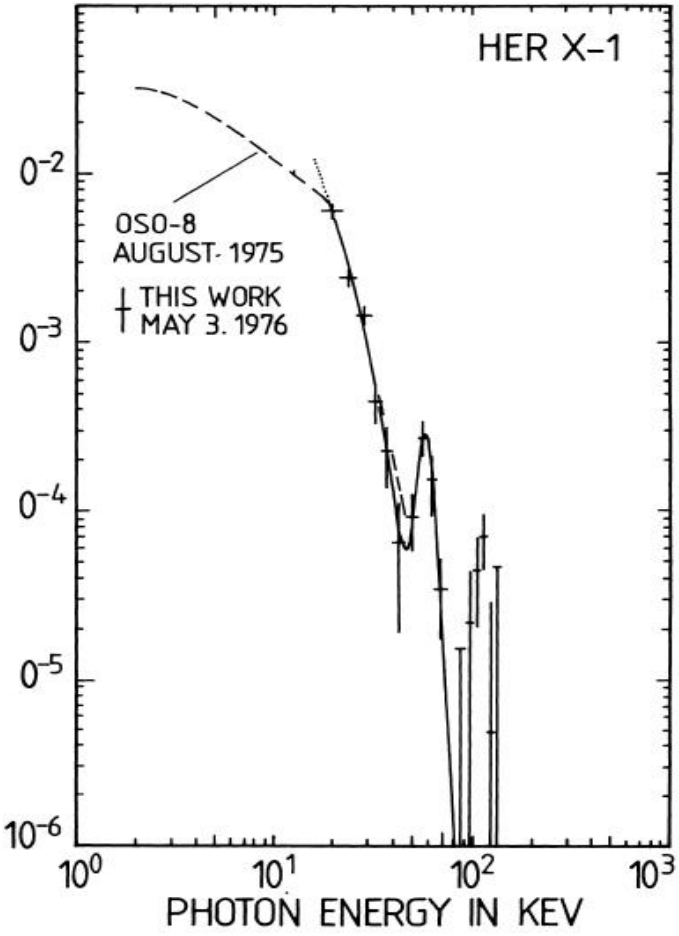
Becker et al. 2007

Cyclotron Resonance Scattering Feature (CRSF)

- CRSFs are generally seen in 10-100 keV spectrum of X-ray pulsars.
- These are absorption like feature, which appear due to resonant scattering of X-ray photons with electrons in quantized levels.
- The energy difference between these levels depends on the strength of magnetic field and given through

  $E_{cyc} = \hbar eB / m_e c = 11.6\ B_{12}$ keV
- Detection of CRSF is a powerful tool to direct estimate the magnetic field of the neutron star.



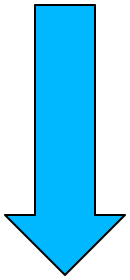


(Truemper et al. 1978)

List of Cyclotron Line Sources

Confirmed

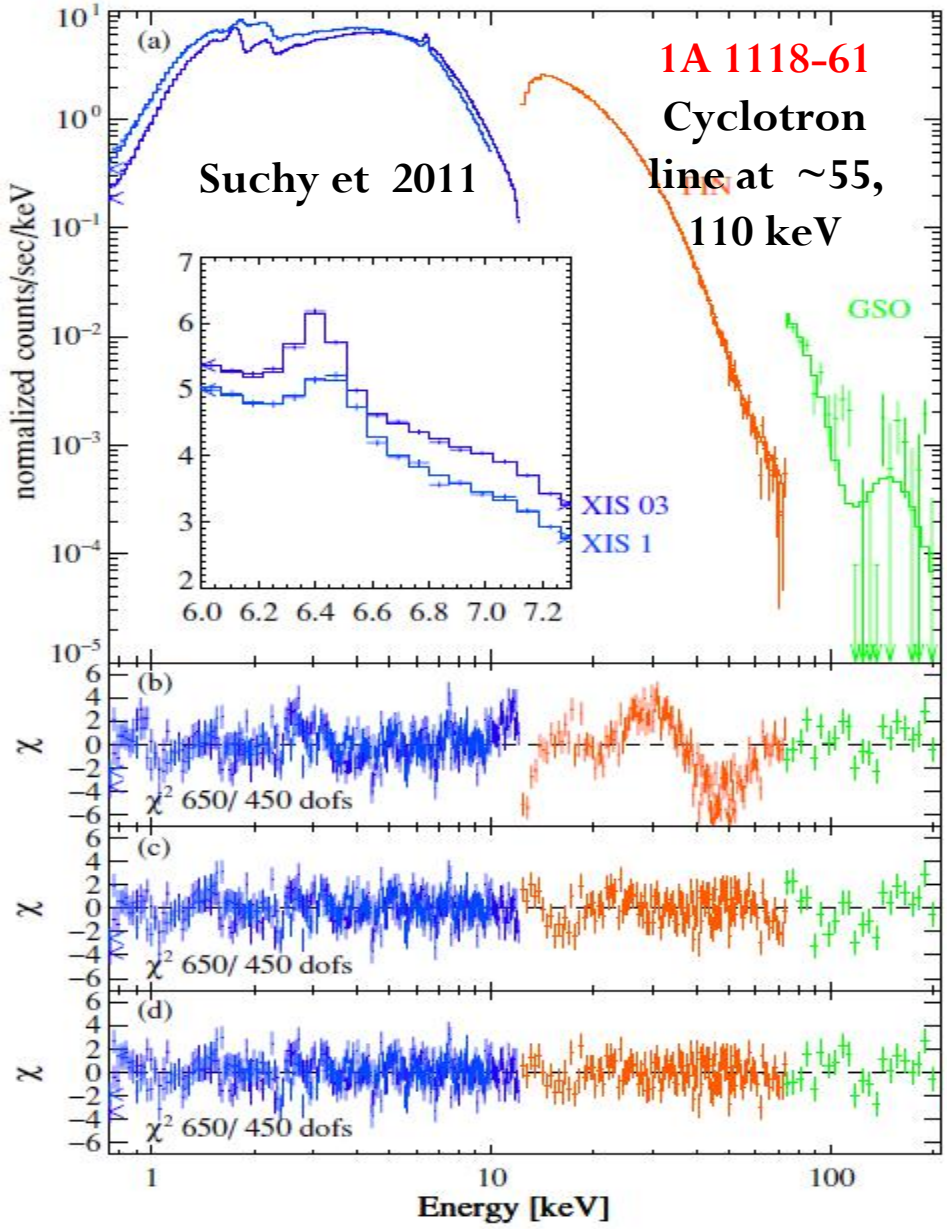
Tentative detection

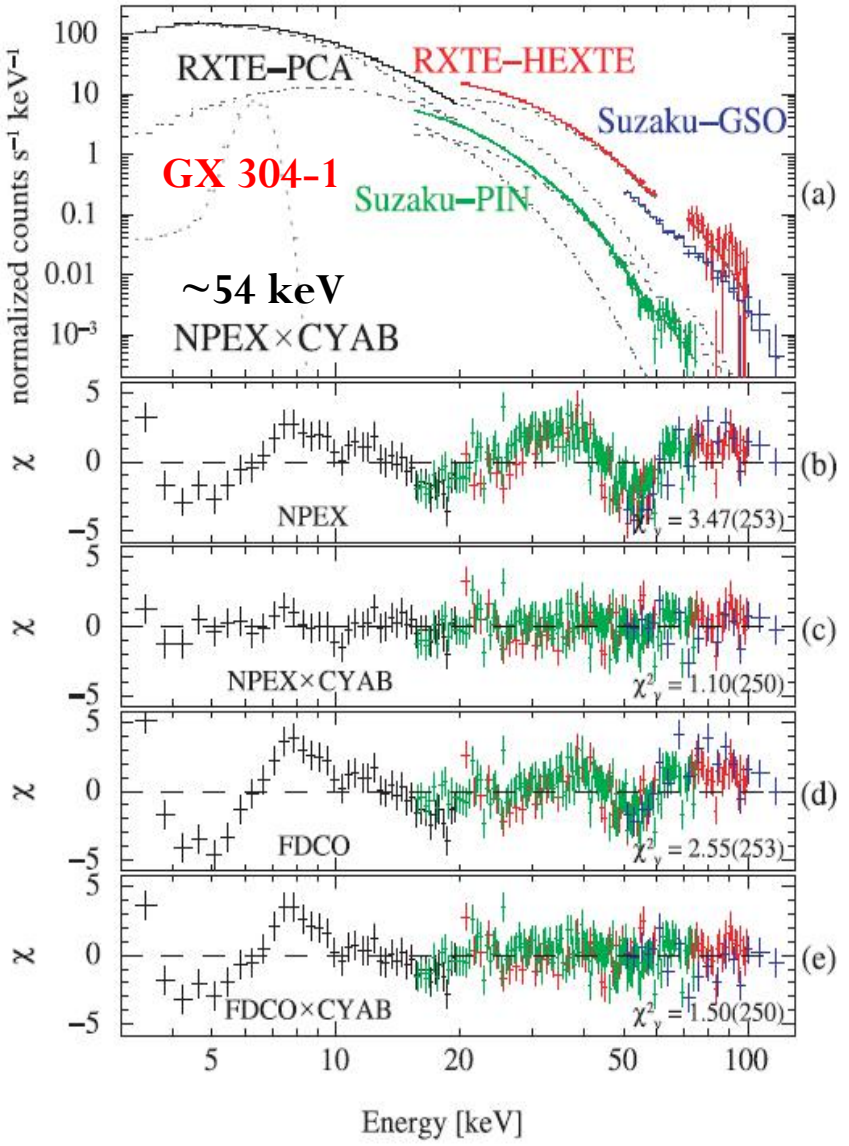


	Source name	CRSFs energies (keV)	Spin period (s)	Orbital period (d)
1	Swift J1626.6-5156	10	15	132.9
2	XMMU J054134.7-682550	10,	61.6	80?
3	KS 1947+300	12.5	18.7	41.5
4	4U 0115+634	14, 24, 36 48, 62	3.61	24.31
5	IGR J17544-2619	17	71.49	4.9
6	4U 1907+09	19, 40	438	838
7	4U 1538-52	22, 47	530	3.73
8	IGR J18179-1621	22	11.8	?
9	2S 1553-542	23.5	9.28	30.6
10	Vela X-1	25, 50	283	8.96
11	V 0332+53	27, 51, 74	4.37	34.25
12	SMC X-2	27	2.37	18
13	Cep X-4	28, 45	66.2	?
14	4U 0352+309 (X Per)	29	837	250.3
15	IGR J16393-4643	29.3	904	4.2
16	Cen X-3	30	4.84	2.09
17	IGR J16493-4348	30	1069	6.7
18	RX J0520.5-6932	31.5	8.04	23.9
19	LS V+44 17	32	202	155?
20	MXB 0656-072	33	160	?
21	XTE J1946+274	36	15.8	169.2
22	4U 1626-67	37	7.66	0.028
23	GX 301-2	37	690	41.48
24	Her X-1	39, 73	1.24	1.7
25	MAXI J1409-619	44, 73, 128	500	?
26	1A 0535+262	45, 100	105	110.6
27	GX 304-1	54	272	132.5
28	1A 1118-615	55, 112?	408	24
29	GRO J1008-57	76	93.5	249.5

1	EXO 2030+375	11? 61?	41.8	46
2	GS 1843+009	20?	29.5	?
3	2S 0114+650	22?, 44?	9600	11.6
4	GX 1+4	34?	138	1161?
5	OAO 1657-415	36?	38	10.2
6	4U 1700-37	37?	?	3.4
7	4U 1909+07	44?	604	4.4
8	LMC X-4	100?	13.5	1.41

Cyclotron features with Suzaku and NuSTAR during outbursts



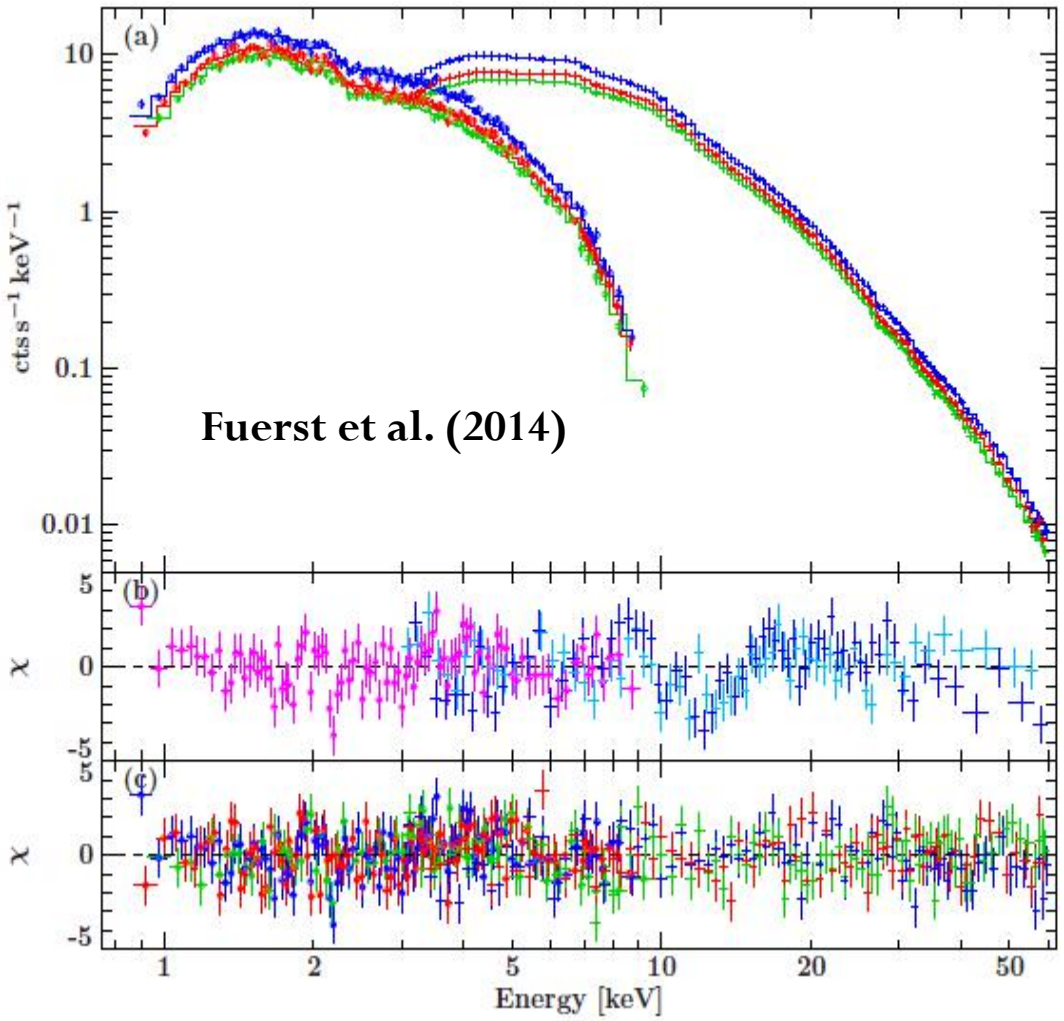


Yamamoto et al. (2011)

Cyclotron features with Suzaku and NuSTAR during outbursts

KS 1947+300

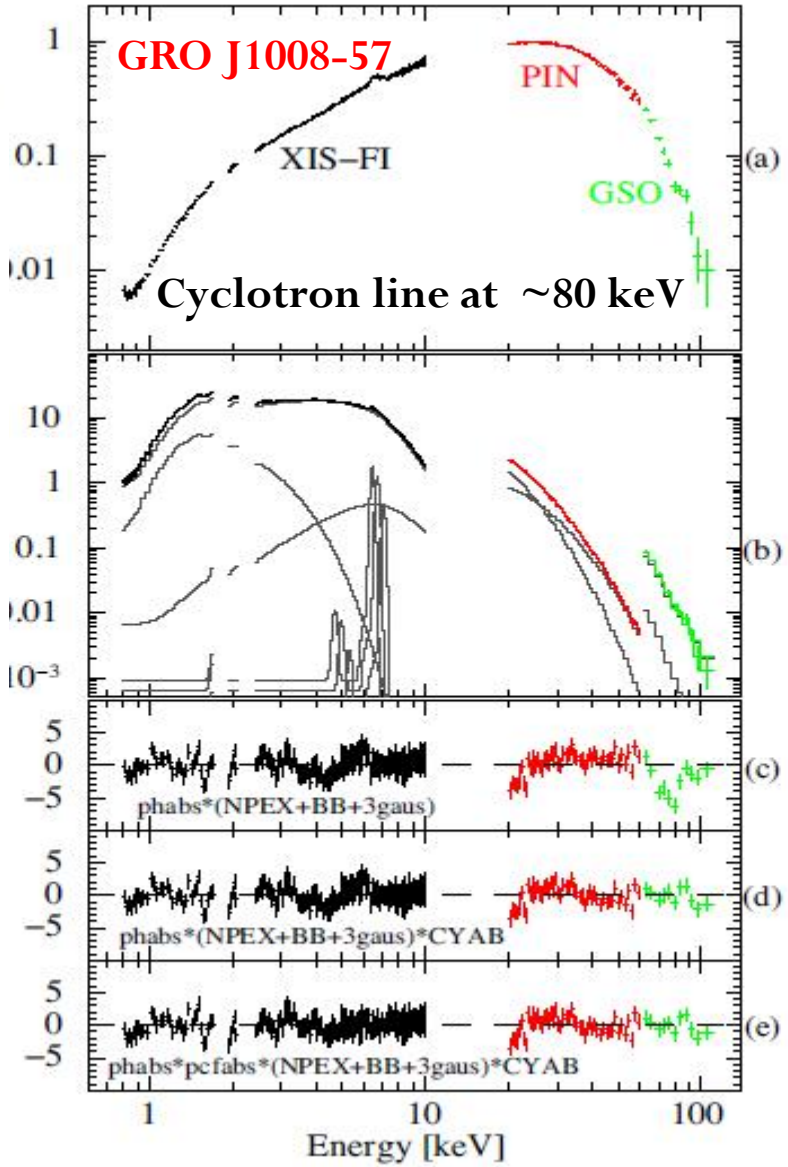
Cyclotron line at ~12 keV



Fuerst et al. (2014)

GRO J1008-57

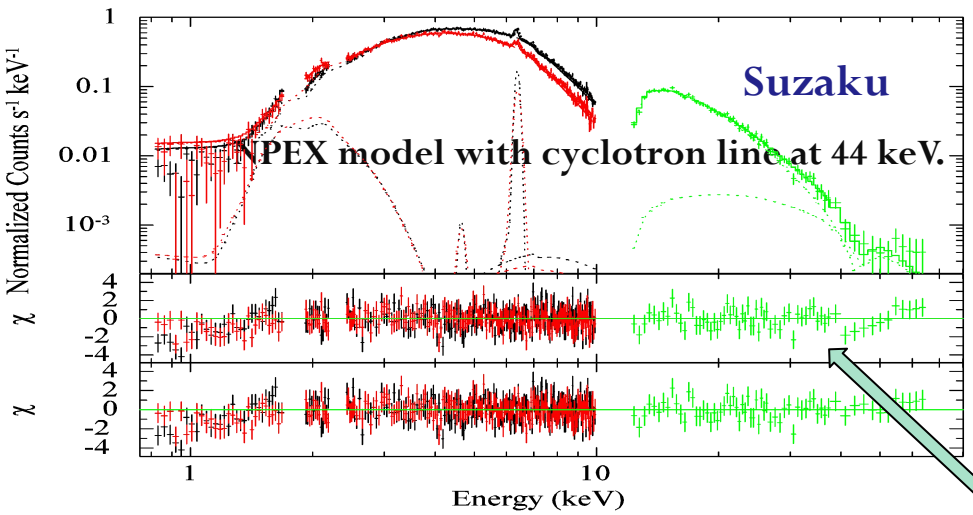
Cyclotron line at ~80 keV



Yamamoto et al. (2011)

Cyclotron line in 4U 1909+07

4U 1909+07



(Jaisawal , Naik, and Paul, 2013)

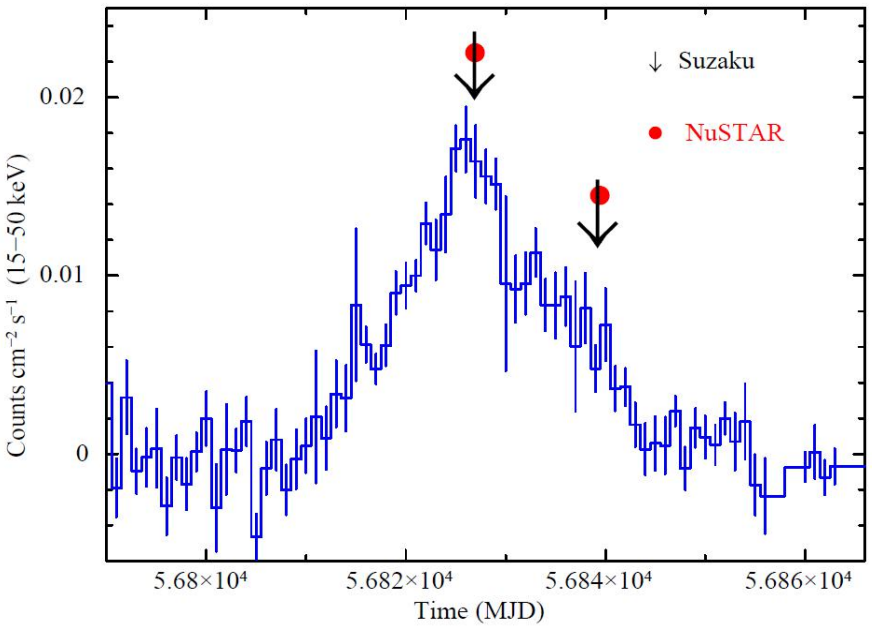
- Poorly studied high mass X-ray binary pulsar.
- Pulsation Period: 604 s (Levine et al. 2004)
- Orbital Period: 4.4 days (Levine et al. 2004)
- Studied Suzaku observation

✓ 1-70 keV spectrum of 4U 1909+07 can describe with partial covering NPEX and high energy cutoff power-law model.

✓ Model independent cyclotron absorption like feature at 44 keV.

✓ Magnetic field of the pulsar is estimated to be 3.8×10^{12} Gauss.

Cyclotron lines in Cep X-4



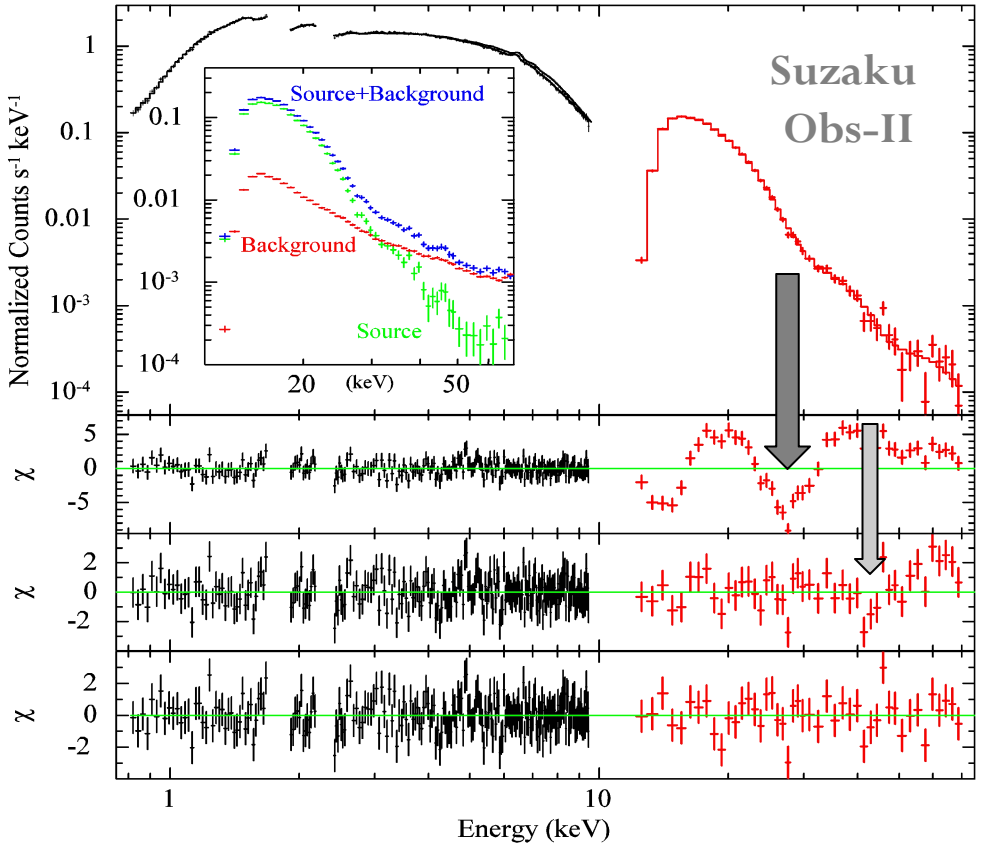
Swift/BAT light curve of Cep X-4 during 2014 June-July outburst.

- **Pulsation period : 66 s (Koyama et al. 1991)**
- **Orbital period – Unknown**
- **Companion is Be star (Roche et al. 1997)**
- **Cyclotron absorption feature reported at ~30 keV (Mihara et al. 1991).**
- **Asymmetric cyclotron line profile during 2014 outburst using NuSTAR (Fuerst et al. 2015).**

We have studied two Suzaku and NuSTAR observations of Cep X-4 during 2014 June-July outburst.

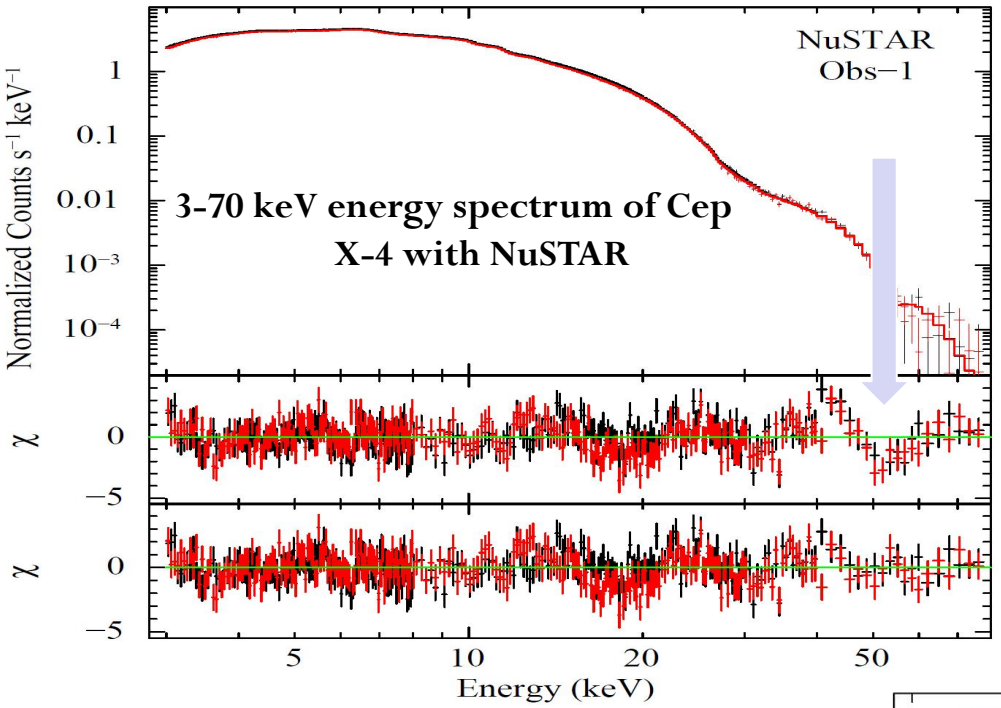
Cyclotron lines in Cep X-4

- The 1-70 keV energy spectrum can describe with NPEX, HECut and FDCut models.
- Apart from 28 keV cyclotron line, an additional absorption like feature seen at 45 keV.
- Model independent feature.
- Close to the twice of cyclotron energy, but less i.e. 1.7+/-0.1
- Identified as first cyclotron harmonic of 28 keV fundamental line.
- The 45 keV absorption feature was detected at >4 sigma level.



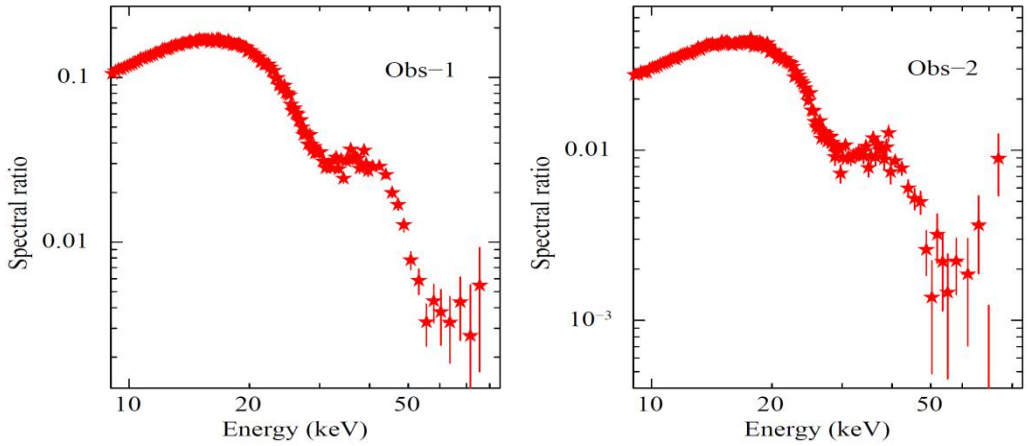
1-70 keV energy spectrum of Cep X-4 with Suzaku (Jaisawal and Naik, 2015)

Cyclotron lines in Cep X-4



We have rechecked NuSTAR data. The first harmonic of cyclotron line was also seen in these observations.

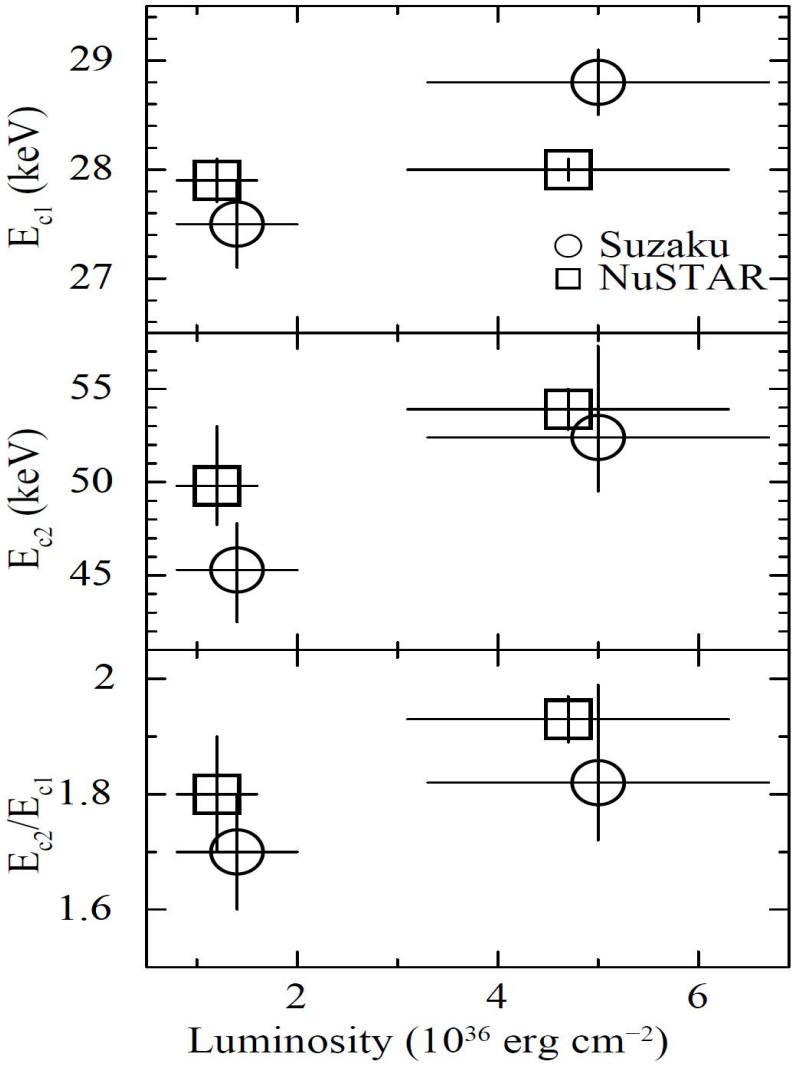
Clear indication of both absorption features in Crab ratio.



Crab ratio of NuSTAR observations

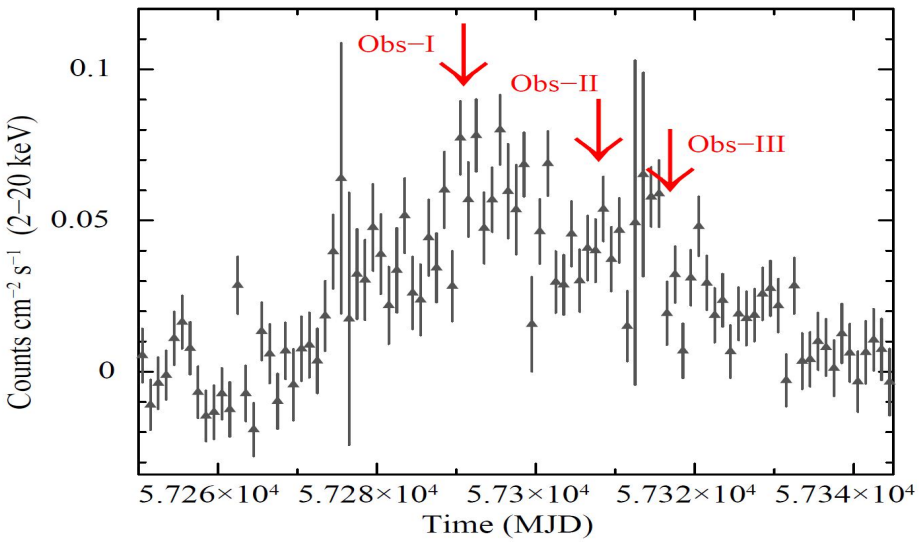
Cyclotron lines in Cep X-4

Luminosity dependent line energy ratio



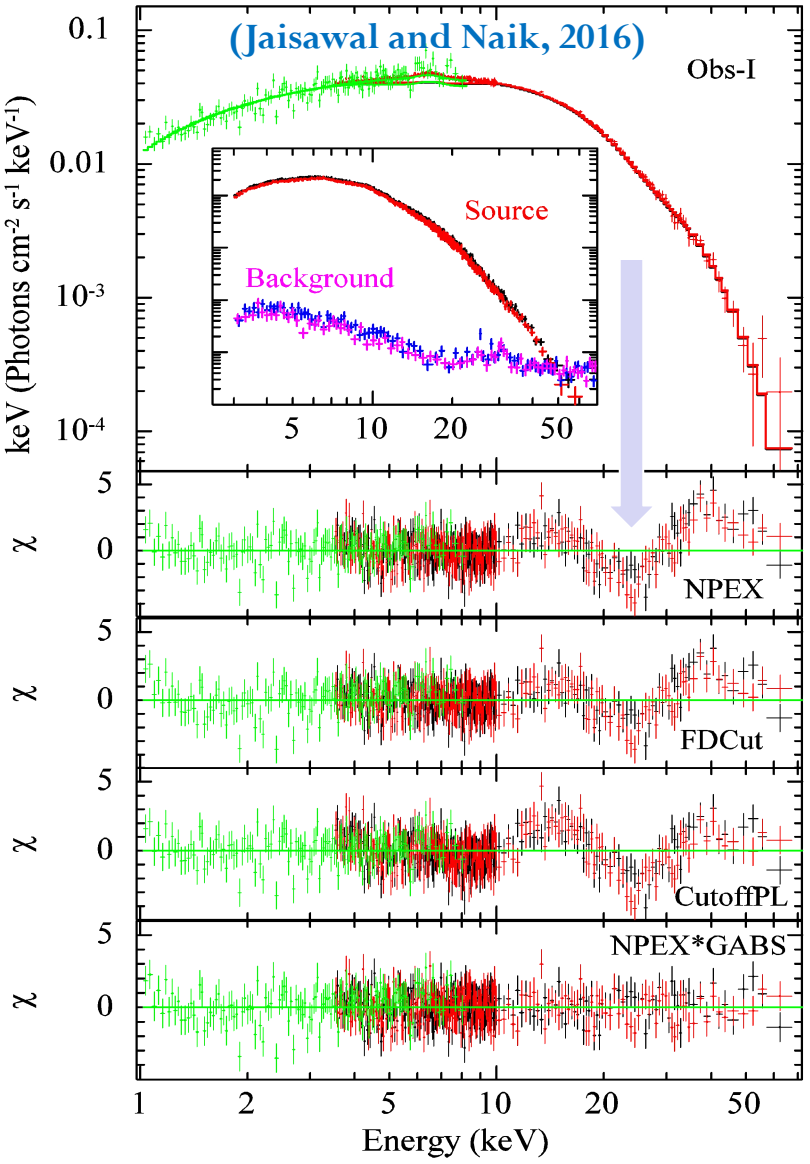
- Fundamental line energy obtained from NuSTAR is nearly constant.
- A significant variation in the first harmonic line energy.
- Luminosity dependent line energy ratio.
- It is possible that both cyclotron lines are forming at different heights in accretion column or viewed at higher angles.

Cyclotron line in SMC X-2



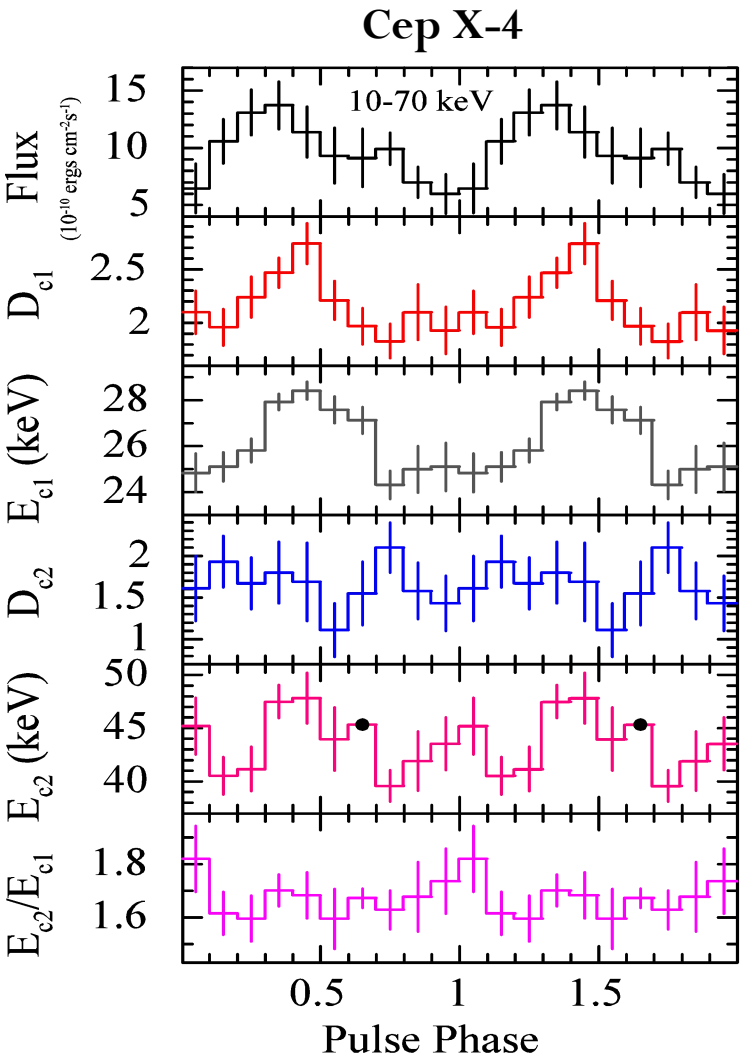
The 2-20 keV MAXI light curve of SMC X-2 during 2015 October outburst.

- **An absorption like feature at ~28 keV is detected in all three observations in a model independent manner.**
- **Magnetic field of the pulsar is estimated to be 2.3x10^{12} Gauss.**
- **Cyclotron line energies is found to be different in all three observations, showing a marginal negative dependence on luminosity (>10^38 erg/s) ⟶ changing line-forming region scenario.**

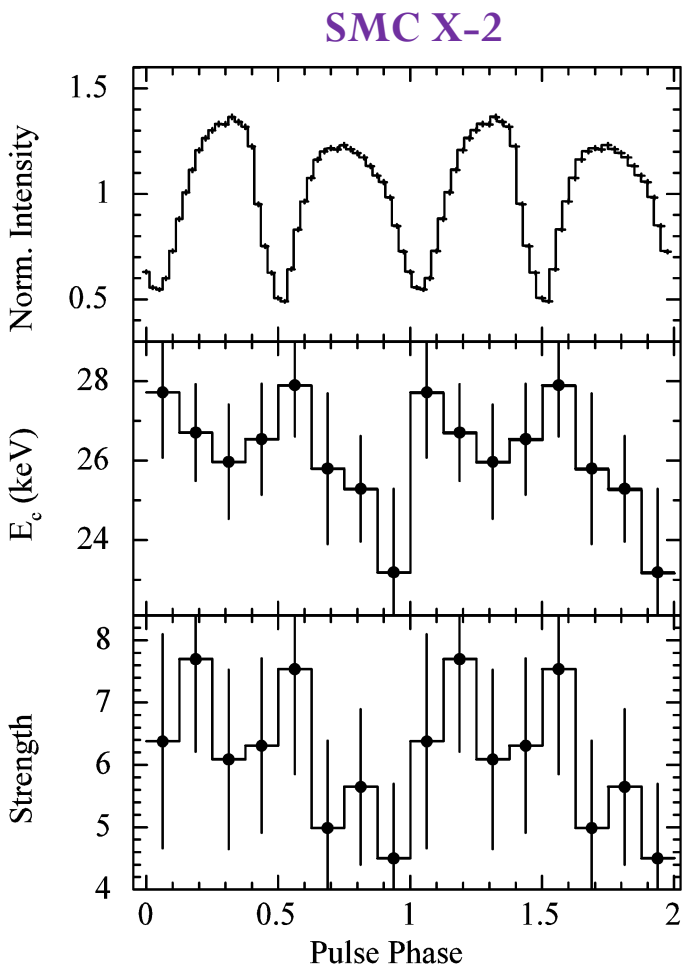


1-70 keV energy spectrum of SMC X-2

Spectral parameters from PHASE RESOLVED SPECTROSCOPY



- The cyclotron line parameters were found to be marginally variable with pulsar phases within 20% of phase-averaged value.
- Changes can be interpreted as the effect of viewing angle or local variation in magnetic field.



Summary and Conclusions

- With hard X-ray capabilities of Suzaku and NuSTAR, the number of cyclotron sources has been increased that helped in understanding of magnetic field and geometry around pulsars.

- We detected cyclotron lines in 4U 1909+07 (fundamental), Cep X-4 (first harmonics), and SMC X-2 (fundamental) for the first time.

- Anharmonicity in cyclotron line energies of Cep X-4, indicating line forming regions are at different height?

- We have also performed the phase-resolved spectroscopy of cyclotron lines in order to map the magnetic field around the pulsars such as Cep X-4 and SMC X-2 .

- The cyclotron parameters were found to be variable within <20 %, indication of local distortion in the magnetic field or effect of viewing angle.

Thanks

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