X-ray intraday variability of the TeV blazar Mrk 421 with *XMM-Newton*

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(Indo-Polish collaboration)

Polish-German WE-Heraeus-Seminar

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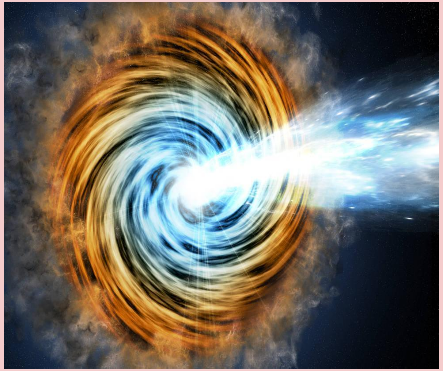

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All results presented here are from this publication:
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X-Ray Intraday Variability of the TeV Blazar Markarian 421 with XMM-Newton

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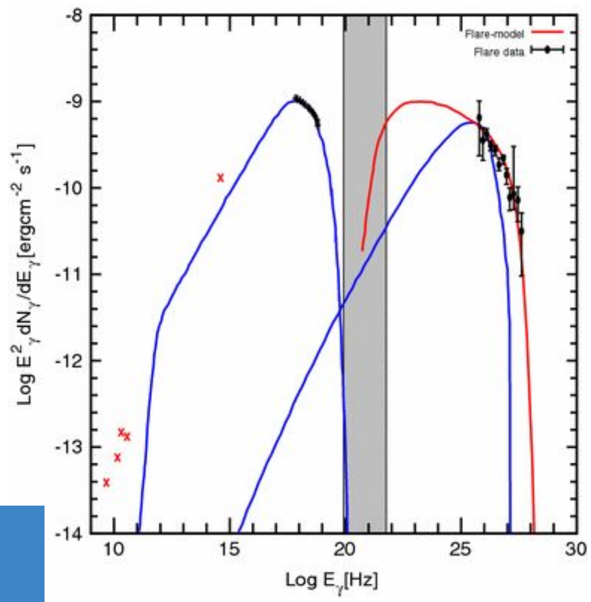
Abstract

Highly variable Markarian 421 is a bright high–synchrotron energy peaked blazar showing a wide featureless nonthermal spectrum, making it a good candidate for our study of intraday flux and spectral variations over time. We analyze its X-ray observations over 17 yr, taken with the EPIC-pn instrument, to probe into the intraday variability properties, focusing on the photon energy band of 0.3–10.0 keV, and its soft (0.3–2.0 keV) and hard (2.0–10.0 keV) subbands. To examine the flux variability, fractional variability amplitudes and minimum variability timescales have been calculated. We also probed into the spectral variability by studying the hardness ratio for each observation, the correlation between the two energy bands, using the discrete correlation function, and inspecting the normalized light curves. The parameters obtained from these methods were studied for any correlations or nonrandom trends. From this work, we speculate on the constraints on the possible particle acceleration and emission processes in the jet, for a better understanding of the processes involving turbulent behavior, except for shocks. A positive discrete correlation function between the two subbands indicates the role of the same electron population in the emission of photons in the two bands. A correlation between the parameter of flux variability and the parameters of spectral variation and lags in the subenergy bands provides the constraints to be considered for any modeling of emission processes.

Markarian 421

- Commonly called as Mkn 421 and Mrk 421; $\alpha_{2000.0}$= 11 h 04 m 27.2 s and $\delta_{2000.0}$ = +38° 12 32 ")
- One of the nearest blazar; z=0.0308
- First detected TeV emission blazar (Punch et al., 1992)
- Synchrotron peak is in X-rays; above 0.1 keV.
- Highly variable in flux and spectra with complex flux variability structures
- Intraday variability is not yet well understood



Credit: Sarira Sahu et al., The European Physical Journal C volume 76, Article number: 127 (2016)

In this work

- Flux variability test over the XMM-Newton observations of Markarian 421
- Correlation of variability in X-ray energy bands Soft (0.2 - 2 keV) and hard (2 - 10 keV)
- Correlation of various variability parameters

Data selection and analysis techniques

- All observations greater than 10 ks were selected. (minimum variability time scale of 5.5ks by Aggrawal et al. (2018), 1.1ks by Chatterjee et al. (2021))
- Fractional variability amplitude (Vaughan, S., Edelson, R., Warwick, R. S., & Uttley, P. 2003, MNRAS, 345, 1271)
- Flux variability timescale (Burbidge, G. R., Jones, T. W., & O’Dell, S. L. 1974, ApJ, 193, 43) (Done by GB)
- Hardness ratio = H / S
- Discrete correlation function (Edelson, R. A., & Krolik, J. H. 1988, ApJ, 333, 646)
- Normalized hard and soft light curves
- Duty cycle (Romero, G. E., Cellone, S. A., & Combi, J. A. 1999, A&AS, 135, 477)

RESULTS

Number	Obs ID	$\bar{x}$	F_{var}(%) Soft (0.3-2.0 keV)	F_{var}(%) Hard (2.0-10.0 keV)	F_{var}(%) Total (0.3-10.0 keV)	τ_{var} (ks)	A	μ (ks)	σ (ks)
1	0099280101	317	9.25 ± 0.07	16.49 ± 0.19	10.16 ± 0.07	3.78 ± 0.41	0.99	0.03	6.5 ± 0.0
2	0099280201	130	9.14 ± 0.08	10.44 ± 0.28	9.17 ± 0.08	4.81 ± 0.65	0.90	2.44	9.8 ± 0.4
3	0099280301	496	3.03 ± 0.05	12.86 ± 0.13	4.12 ± 0.04	4.50 ± 0.54	0.77	-0.19	2.3 ± 0.1
4	0136540101	438	5.09 ± 0.06	12.45 ± 0.19	5.76 ± 0.06	3.41 ± 0.33	0.88	-0.21	1.6 ± 0.2
5	0136541001	291	3.41 ± 0.03	6.61 ± 0.09	3.62 ± 0.02	4.19 ± 0.31	0.83	-1.11	4.7 ± 0.7
6	0158970101	329	6.27 ± 0.07	8.78 ± 0.28	6.35 ± 0.07	2.51 ± 0.24	0.67	2.56	7.9 ± 0.7
7	0150498701	694	7.61 ± 0.05	17.61 ± 0.17	8.29 ± 0.05	2.96 ± 0.16	0.77	1.71	7.4 ± 0.6
8	0162960101	362	2.79 ± 0.08	4.62 ± 0.26	2.91 ± 0.08	2.61 ± 0.27	0.71	0.04	4.5 ± 1.1
9	0158971201	850	9.51 ± 0.03	22.85 ± 0.06	11.61 ± 0.02	5.96 ± 0.52	0.94	-0.38	2.2 ± 0.2
10	0153951201	678	4.30 ± 0.19	6.41 ± 0.59	4.50 ± 0.18	7.02 ± 0.59	0.89	0.23	3.1 ± 0.2
11	0158971301	748	11.11 ± 0.04	15.11 ± 0.11	11.53 ± 0.04	4.53 ± 0.33	0.96	1.31	19.6 ± 2.2
12	0302180101	537	3.87 ± 0.02	8.93 ± 0.07	4.43 ± 0.02	10.59 ± 0.79	0.87	-0.19	3.9 ± 1.2
13	0411080301	822	3.69 ± 0.05	8.19 ± 0.14	4.33 ± 0.05	5.46 ± 0.53	0.88	0.31	5.3 ± 0.3
14	0411080701	302	1.13 ± 0.05	2.59 ± 0.22	1.18 ± 0.06	5.78 ± 0.45	0.62	-0.94	5.9 ± 2.8
15	0510610101	265	1.21 ± 0.04	3.36 ± 0.22	1.32 ± 0.04	4.69 ± 0.34	0.76	-0.24	3.4 ± 0.5
16	0510610201	276	1.85 ± 0.05	3.91 ± 0.21	1.98 ± 0.04	7.60 ± 0.69	0.84	0.23	5.9 ± 0.5
17	0502030101	703	6.38 ± 0.02	10.19 ± 0.08	6.67 ± 0.02	9.60 ± 0.66	0.89	-0.17	2.8 ± 0.6
18	0670920301	673	2.44 ± 0.09	3.84 ± 0.36	2.49 ± 0.09	1.68 ± 0.15	0.77	-0.81	3.1 ± 0.1
19	0670920401	127	10.76 ± 0.11	11.69 ± 0.77	10.78 ± 0.12	1.03 ± 0.07	0.76	-0.21	1.6 ± 0.2
20	0670920501	626	1.64 ± 0.04	3.78 ± 0.17	1.76 ± 0.05	4.91 ± 0.29	0.77	0.15	1.3 ± 0.2
21	0658801301	283	5.97 ± 0.07	9.24 ± 0.18	6.38 ± 0.07	1.92 ± 0.19	0.97	0.05	10.6 ± 0.1
22	0658801801	230	6.13 ± 0.08	14.02 ± 0.34	6.65 ± 0.08	2.74 ± 0.39	0.91	0.57	4.3 ± 0.5
23	0658802301	314	3.16 ± 0.13	3.92 ± 0.51	3.21 ± 0.13	1.64 ± 0.26	0.65	-1.46	6.9 ± 0.4
24	0791780101	76	0.47 ± 0.12	2.21 ± 0.43	0.61 ± 0.11	2.01 ± 0.23	0.18	0.23	0.9 ± 0.2
25	0791780601	420	0.74 ± 0.09	1.09 ± 0.24	0.78 ± 0.08	4.92 ± 0.56	0.46	-0.45	1.1 ± 0.2

- 23 observations are variable
- Duty cycle ~ 96%

Observation with highest variability

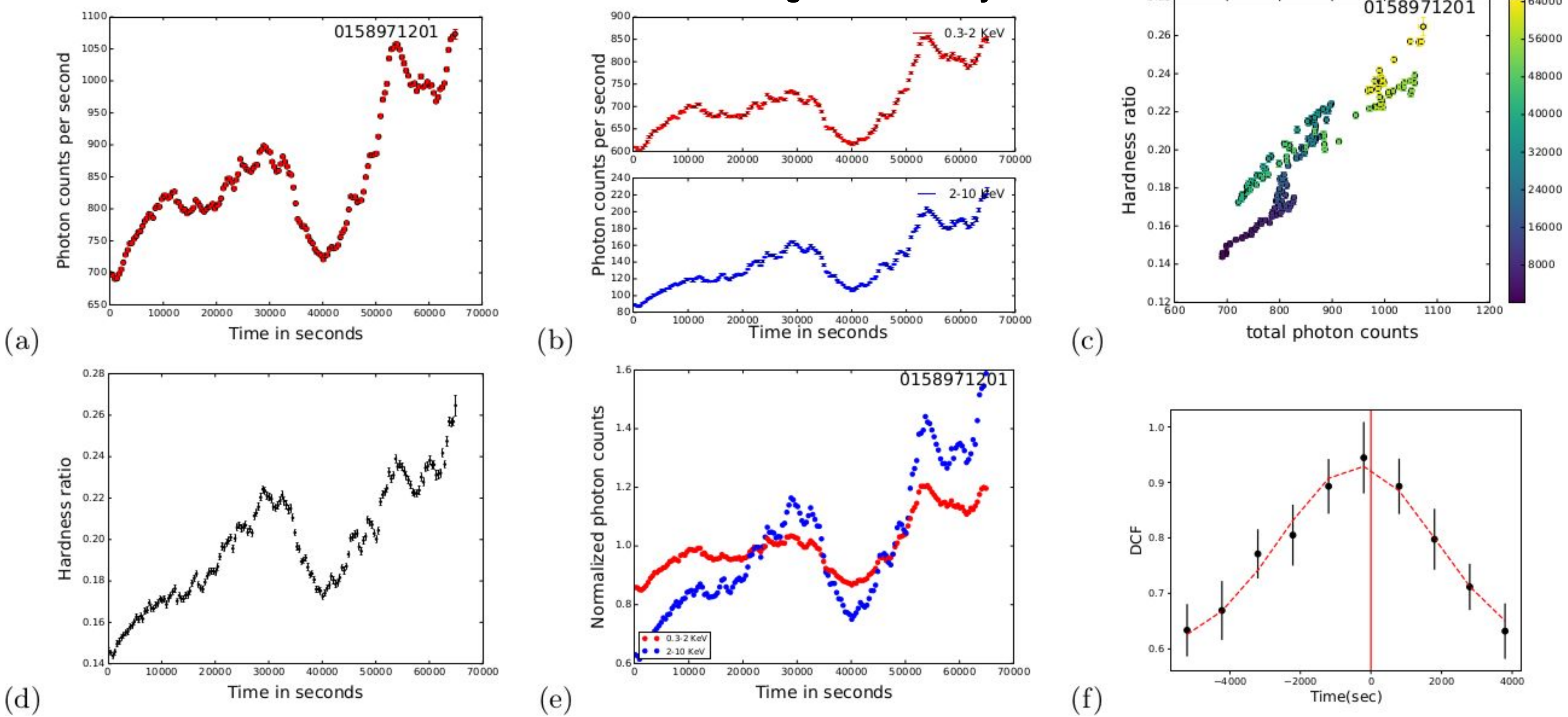


Figure 1. (a) Light curve in the total energy range (0.3-10.0 keV); (b) light curves in hard and soft energy bands; (c) hardness ratio vs. intensity (HR–I) diagram; (d) HR vs. time; (e) normalized light curves in the hard and the soft energy bands (points without error bars for the picture clarity); (f) a discrete correlation function (DCF). In panel © the observational time is coded with a colour - dark blue for the beginning and yellow for the end of observation. Variability of 11.6% in total band and ~22% in hard band.

Observations with no variability

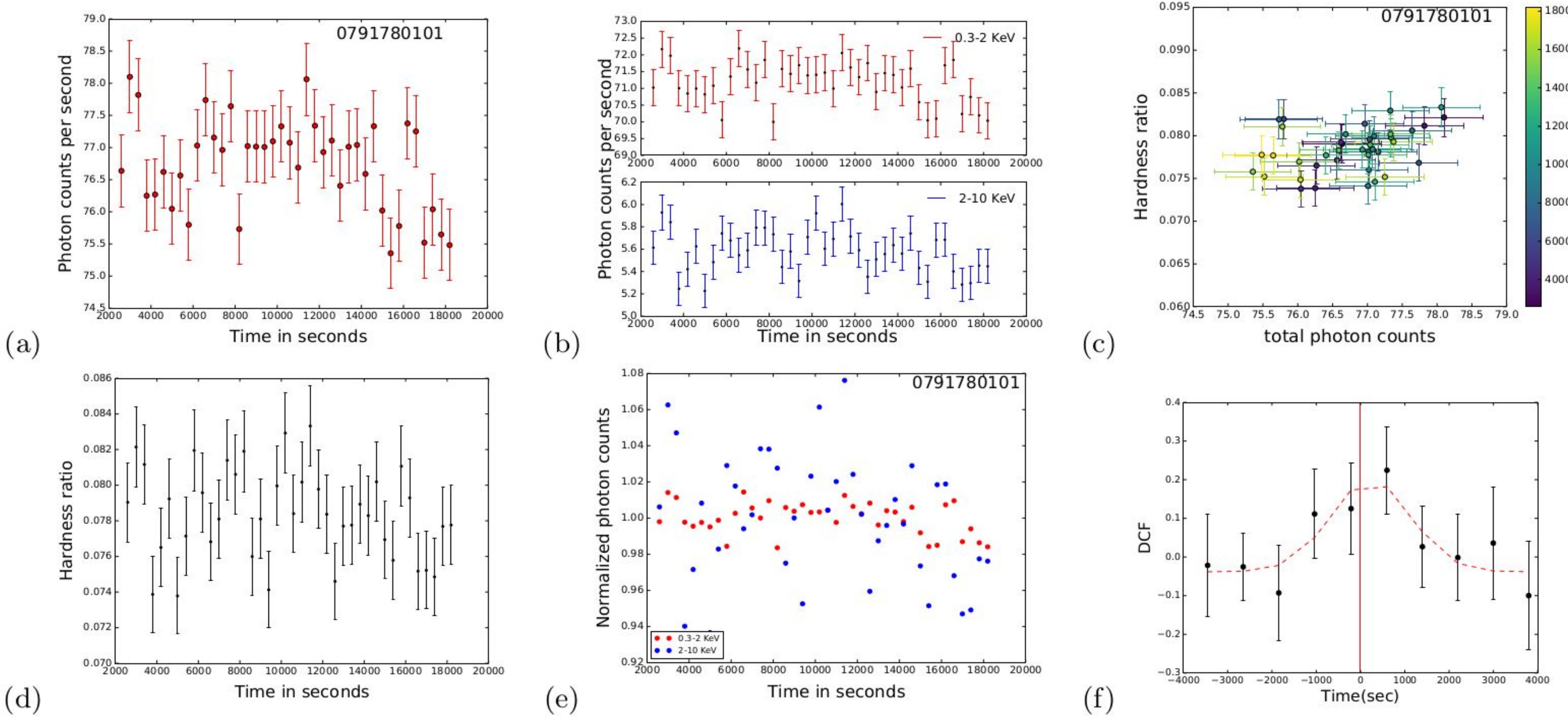


Figure 2: As described in figure 1. Observation time: 17.5 ks

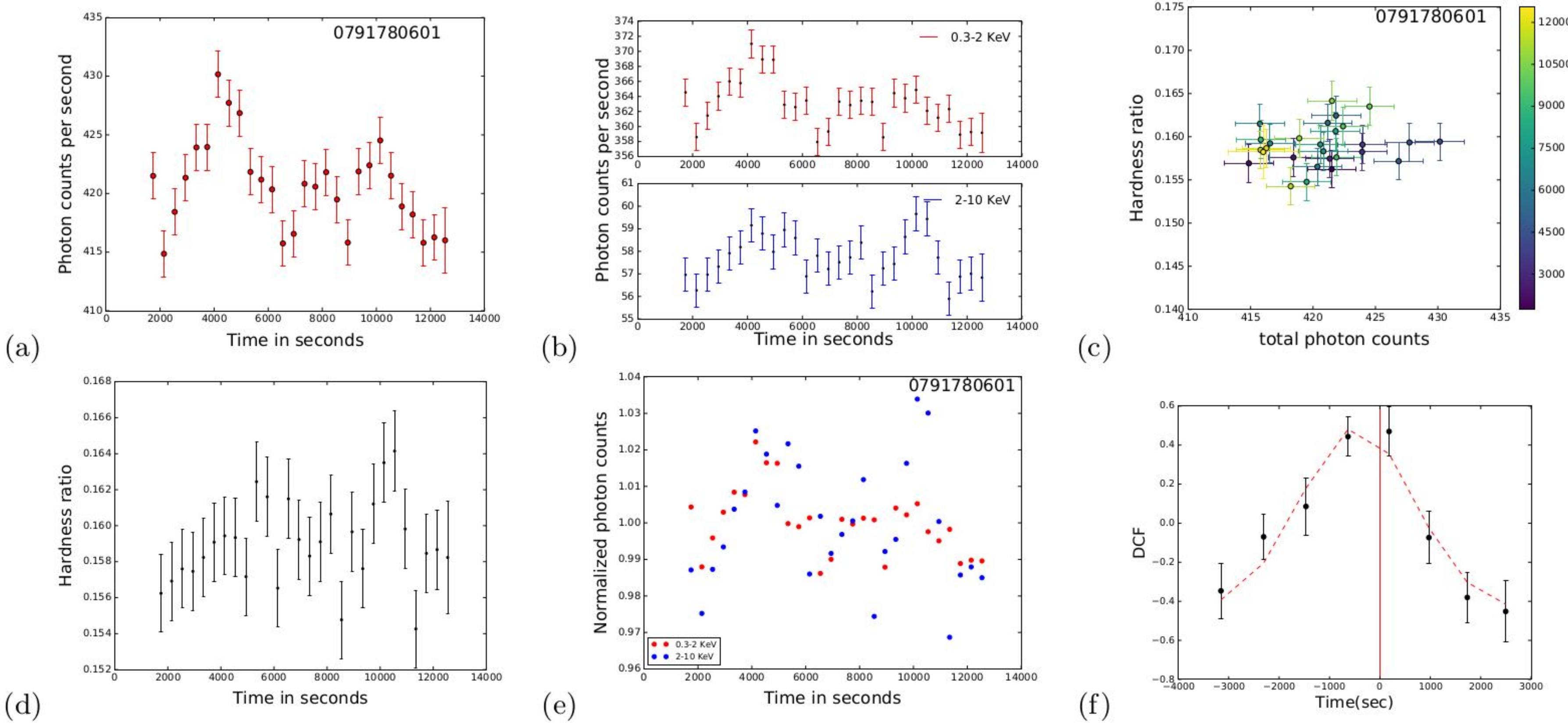
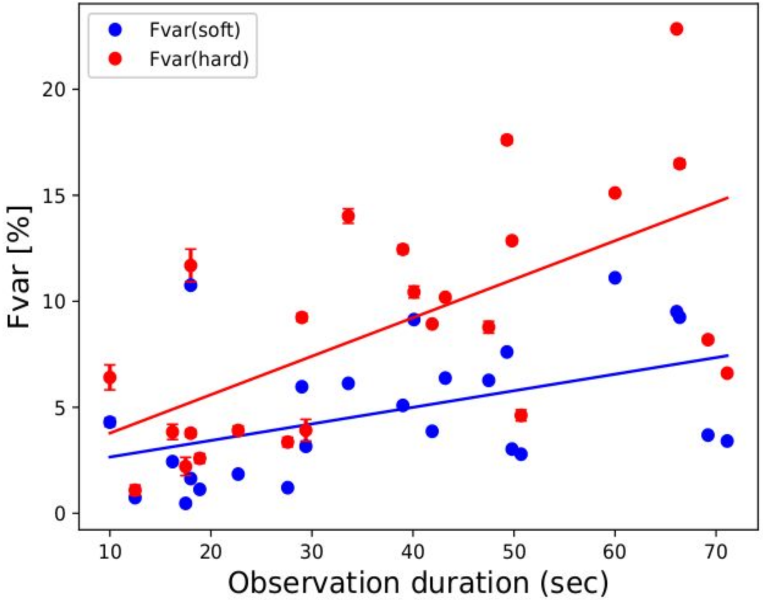


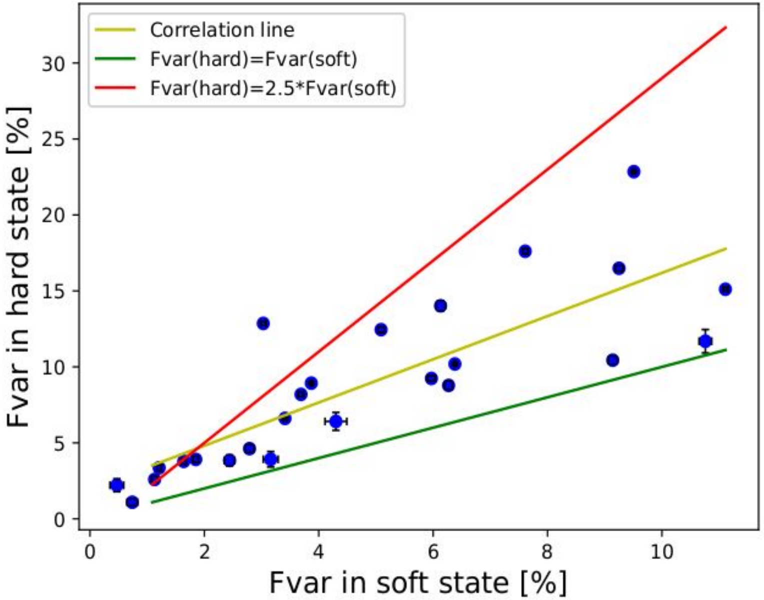
Figure 3: As described in figure 1. Observation time: 12.5 ks

- We found the IDV duty cycle to be 96%, but some level of variability is noted in all data.
- The HR analysis for our soft versus hard bands shows the similar pattern as the light curve

- The fractional variability amplitude depends on the studied X-ray energy range. it is always higher in the hard band than in the soft band (and in the total energy band). Peretz & Behar (2018) did a classification of AGNs on the basis of the X-ray variability and reported the same for RL AGN.



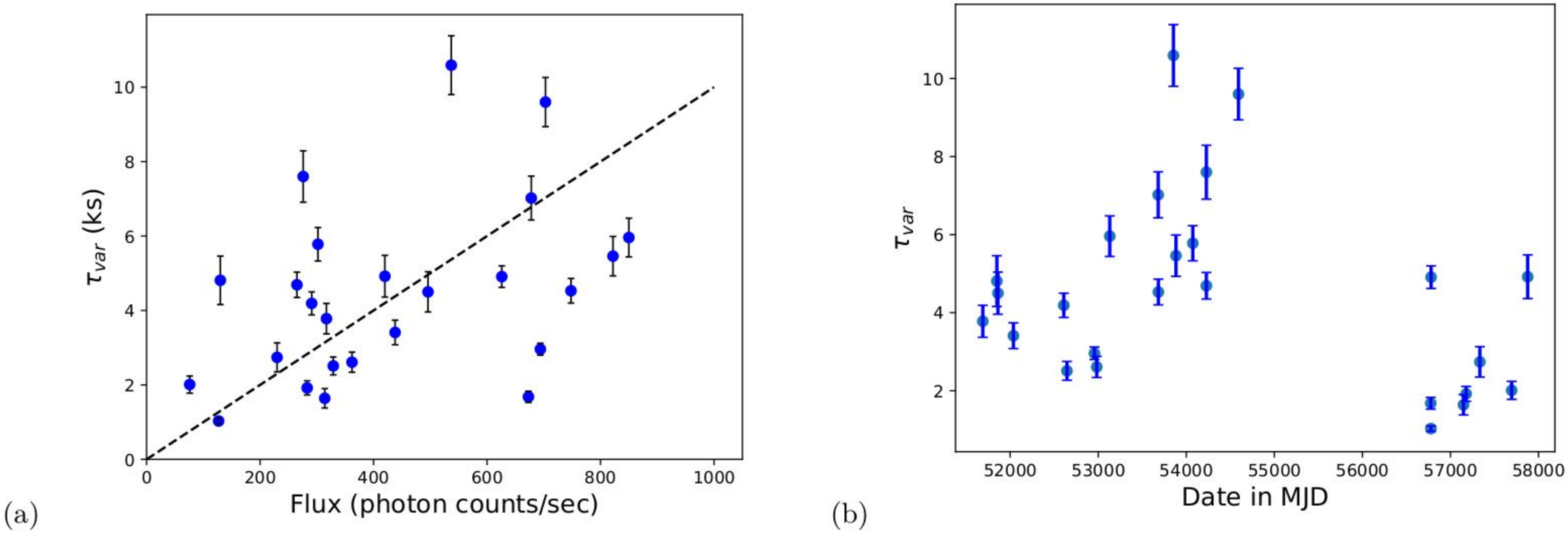
(a)



(b)

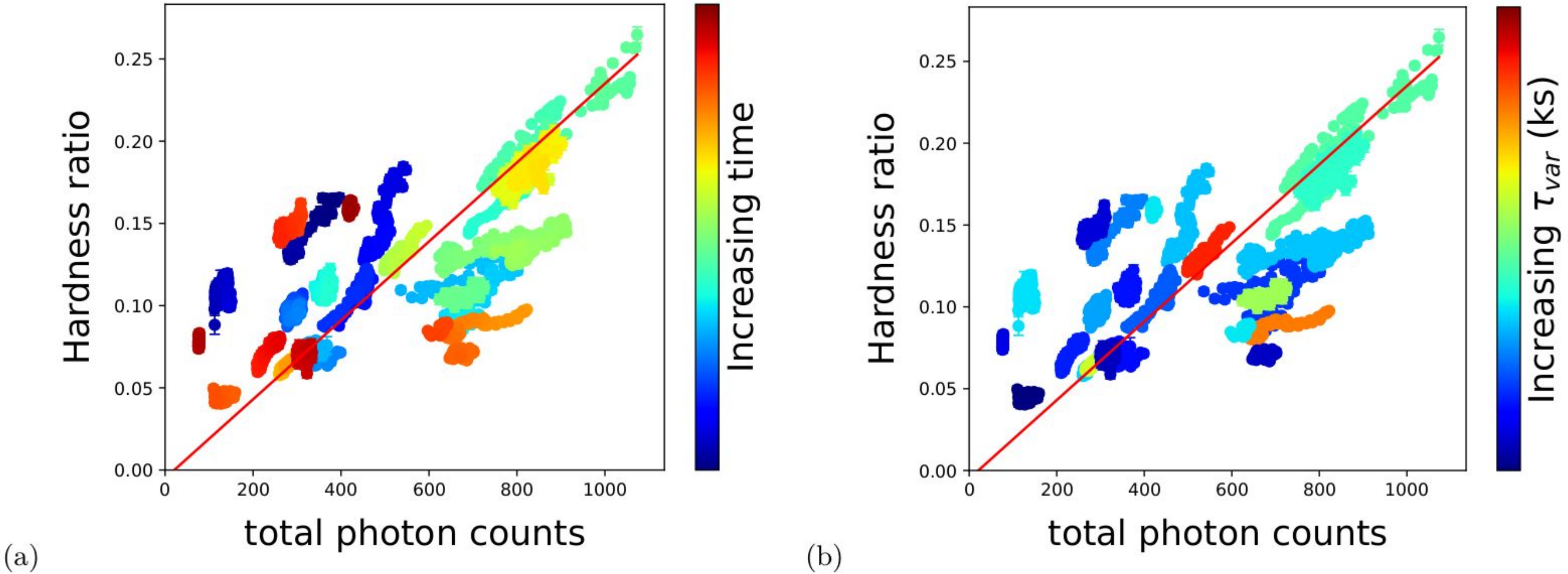
(a) Fractional variability F var in the soft and the hard energy bands plotted versus duration of observation, the fitted correlation lines are provided for both distributions. (b) F var in the hard versus the soft band. The lines Fvar (hard) = Fvar (soft) and Fvar (hard) = 2.5*Fvar(soft) are provided for reference.

- The total energy weighted minimum variability timescales for all observation IDs occur in the range from 1.03 ks to 10.59 ks.

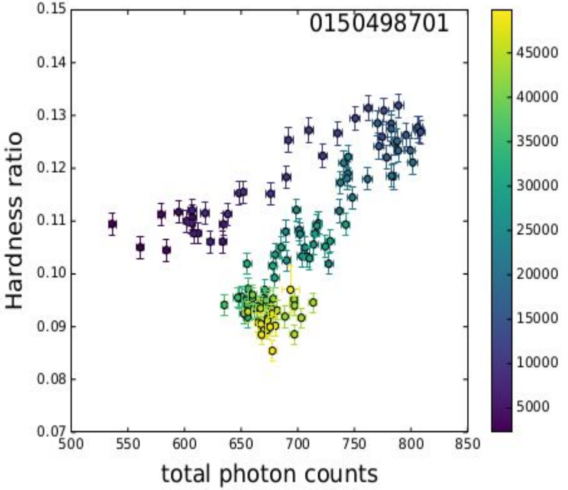


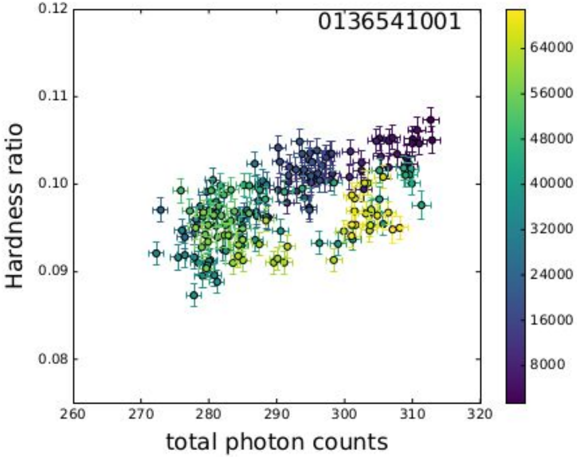
(a) A plot of τ_{var} vs. the mean photon flux x for all observations. (b) The minimum variability time scale τ_{var} plotted against observation date given in MJD for all observations.

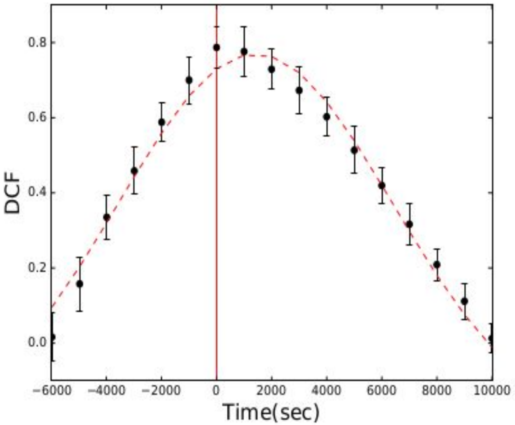
- **A clear harder when brighter behaviour**
- The HR analysis for our hard versus soft bands shows the similar pattern as the light curve
- In numerous observations one may note formation of clockwise and anti-clockwise loops in HR-I diagrams.

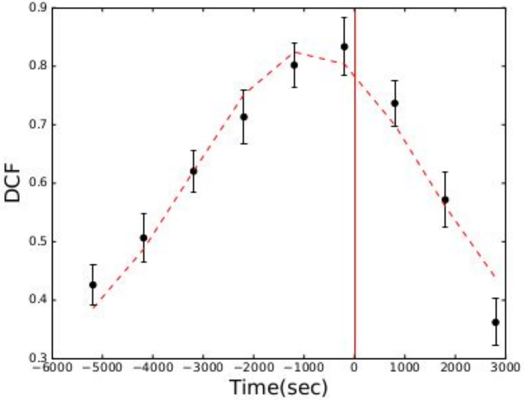


HR-I diagram of all plots combined into one with the color bar (a) depicting the chronology of the observation, (b) showing distribution of the derived τ_{var} within observations.

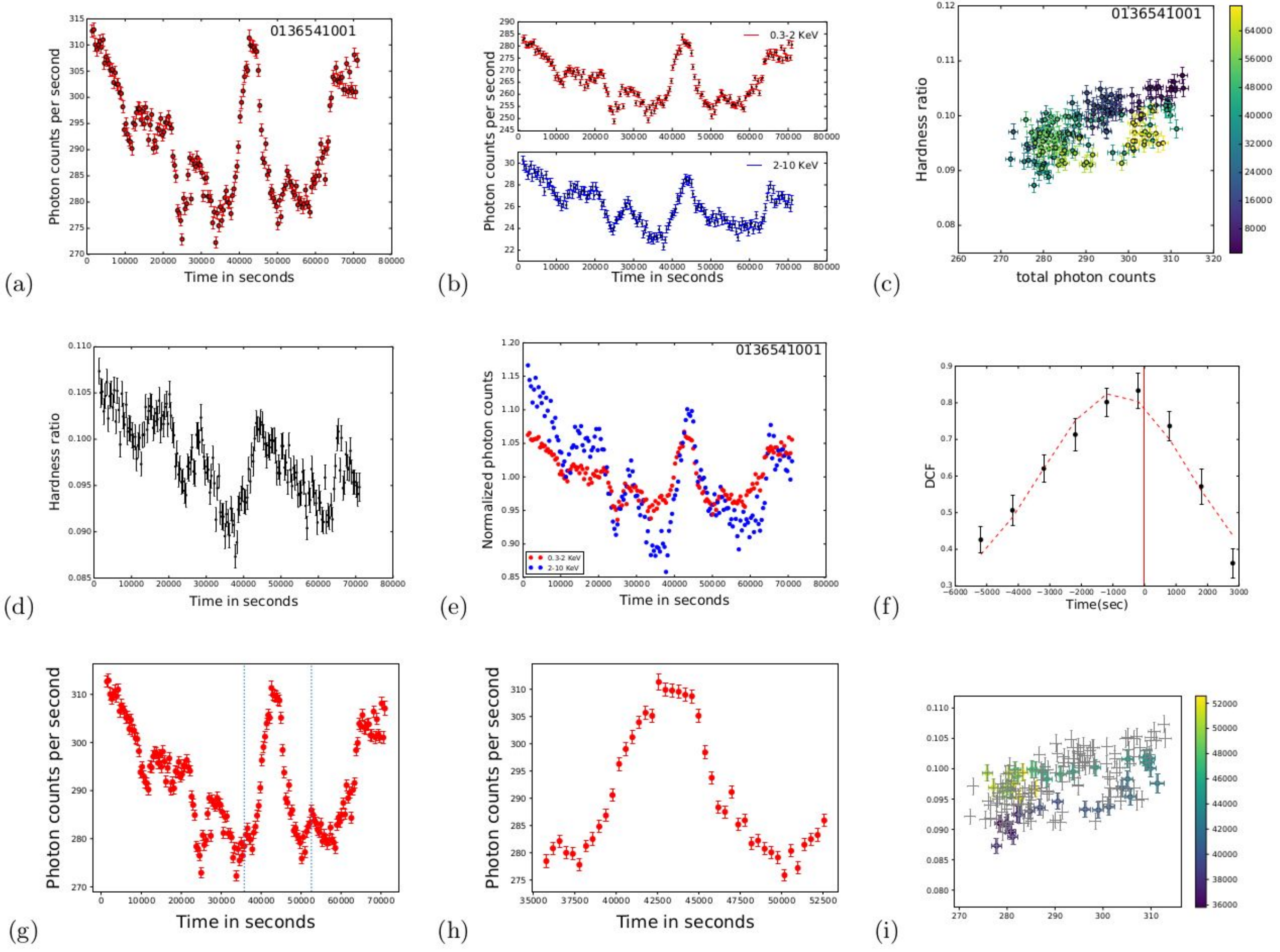








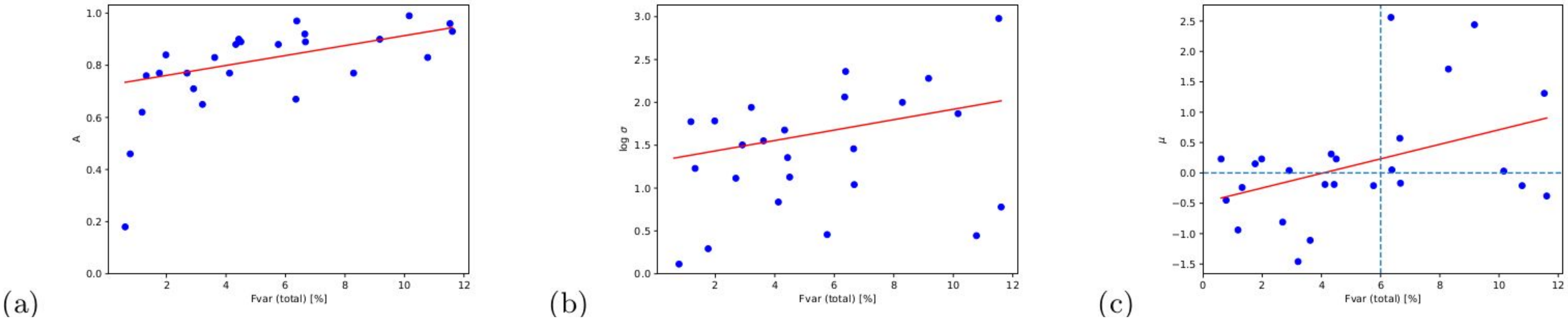
- Observations forming a clockwise loop in the HR-I diagram has a positive time lag while those forming an anti-clockwise loop has a negative lag. Zhang et al. 2002, 2006; Fossati et al. 2000)
- The registered larger time shifts μ of DCF maxima may be related with different evolution on longer time scales of photon fluxes in the different energy bands.
- Zhang et al. (2006) explained the direction of loops on the basis of energy dependent acceleration and cooling timescales of the emission particles, by somewhat arbitrarily varying these parameters for hard and soft photons. We prefer to think about possible physical source for such observations related to the complexes of relativistic magnetic field reconnection regions and relativistic turbulence within the jet volume modulated by the fluctuating jet density (or shocks).



The reversal of loop direction for the flaring part from the entire observation's HR-I loop direction.

Date of obs: 1 December 2000

- The measured time lags between (0.3 - 2.0) keV (soft) and (2.0 - 10.0) keV (hard) bands from the DCF maximum fitting do not reveal any constant pattern.
- We observe that occurrence of the big lags in soft or hard photons is related to the degree of flux variability.



Fractional variability versus the parameters of the Gaussian fits of the DCF maximum: (a) the amplitude A, (b) the width σ, (c) the time lag μ. Red lines represent linear fits to the presented distributions, without considering the two ”non-variable” outliers with lowest Fvar .

Conclusions

- Shock acceleration- In shocks high energy particles require longer times for acceleration and our observed events with high energy emission preceding the low energy one is in contradiction to such model.
- Variability at such short timescale may be caused due to turbulence.
- Magnetic reconnection- still symmetry of some individual flares is difficult to explain if the reconnection is not modulated by an external symmetric process.
- In our view such models could fit the varying emission details in different observations if the emission is generated by modulated ensemble of numerous magnetic reconnection processes operating with time scales much shorter than the flares we observe.
- Any model used to explain the blazar emission should be verified with simultaneous MWL observations.

Acknowledgements
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Back-up

Obs. ID	Date of Obs. dd−mm−yyyy	Window mode	Obs. duration (ks)	Pile up	Filter
0099280101	25−05−2000	Small	66.4	yes	Thick
0099280201	01−11−2000	Small	40.1	yes	Thick
0099280301	13−11−2000	Small	49.8	yes	Thick
0136540101	08−05−2001	Small	39.0	yes	Thin 1
0136541001	01−12−2002	Timing	71.1	no	Medium
0158970101	01−06−2003	Small	47.5	yes	Thin 1
0150498701	14−11−2003	Timing	49.3	no	Thin 1
0162960101	10−12−2003	Small	50.7	yes	Medium
0158971201	06−05−2004	Timing	66.1	no	Medium
0153951201	07−11−2005	Timing	10.0	no	Thin 1
0158971301	09−11−2005	Timing	60.0	no	Thick
0302180101	29−04−2006	Timing	41.9	no	Thin 1
0411080301	28−05−2006	Small	69.2	yes	Medium
0411080701	05−12−2006	Timing	18.9	no	Medium
0510610101	08−05−2007	Timing	27.6	no	Medium
0510610201	08−05−2007	Timing	22.7	no	Medium
0502030101	07−05−2008	Timing	43.2	no	Thin 1
0670920301	29−04−2014	Timing	16.2	no	Thin 1
0670920401	01−05−2014	Timing	18.0	no	Thin 1
0670920501	03−05−2014	Timing	18.0	no	Thin 1
0658801301	05−06−2015	Small	29.0	yes	Thick
0658801801	08−11−2015	Small	33.6	yes	Thick
0658802301	06−05−2016	Small	29.4	yes	Thick
0791780101	03−11−2016	Small	17.5	no	Thick
0791780601	04−05−2017	Small	12.5	yes	Thick