Observations of Markarian 421 with VERITAS

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Abstract

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The BL Lacertae object Markarian 421 is a variable gamma ray source and can flare to many times that of the Crab Nebula. This source is observed by VERITAS, the Very Energetic Radiation Imaging Telescope Array System, which consists of four imaging atmospheric Cherenkov telescopes and is located in southern Arizona. During the 2007/2008 observing season we observed the source for over 30 hours and report the statistical significance of gamma rays to be 235 standard deviations. We correlate our results with x ray data and summarize the mechanisms which are thought to cause gamma ray emission.

Keywords: Markarian 421, variable source, VERITAS, gamma ray

Introduction

Markarian 421 is located in Ursa Major, about 360 million light years away, in a giant elliptical galaxy. It was the first discovered extragalactic gamma ray source by the Whipple 10 meter Telescope in 1992 (Punch, et al. 1992) and it has been observed at radio (Owen, et al. 1978, Zhang & Baath 1990, Mufson, et al. 1990), optical (Mufson, et al. 1990, Maza, 1978), and x-ray (Mufson, et al. 1990, Mushotzky, et al. 1979, George, et al. 1988) frequencies as well.

Markarian 421 is a greatly variable source flaring on timescales from minutes to days. The flux, measured in gamma rays per minute, can double within 15 minutes (Gaidos, et al. 1996). Markarian 421 can flare to ten times that of the Crab Nebula. The Crab Nebula is considered the standard candle in gamma ray observations and all observations are compared to its constancy (Meyer, et al. 2010). Flaring is often seen correlated with increased flux in the x-ray energies, although such correlation is generally loose at best (Blazejowski, et al. 2005).

Markarian 421 is a BL Lacertae object. BL Lacertae objects are included in the classification of blazars. Markarian 421 was the first discovered blazar and at z=.031 remains the nearest blazar to the Earth (Blazejowski, et al. 2005). Blazars, in turn, are in the family of active galactic nuclei. Emission from an active galactic nucleus is thought to be powered by accretion onto a super massive black hole. This happens when orbiting gas and dust from the accretion disk lose angular momentum and fall into the black hole (Tluczykont 2010). Gamma rays are found in the resulting jets of high energy particles which are accelerated near the black hole. These high energy jets, as seen in blue in Figure 1, are perpendicular to the accretion disk, as seen in orange, and opposite to each other. What sets BL Lacertae objects apart from other types of blazars is that the jets are directed into our line of sight. It has been postulated that all blazars are the same, it is just their orientation that differs (Blazejowski, et al. 2005).

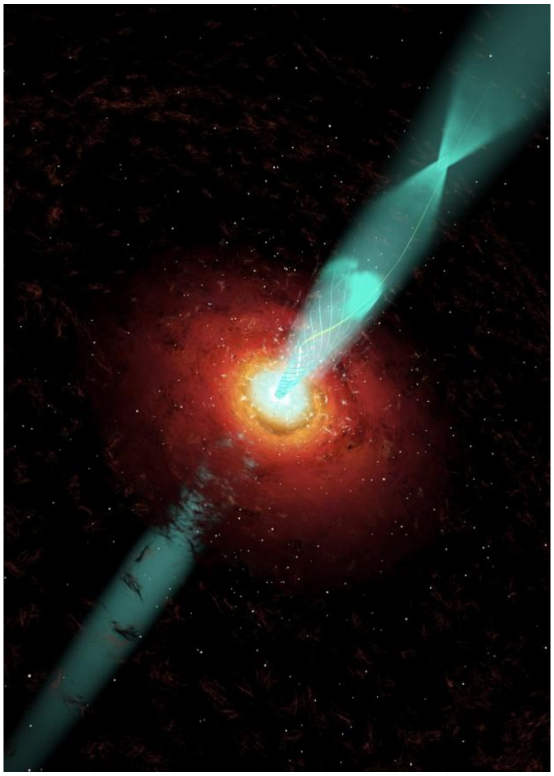

Figure 1: An Illustration of the high energy jets from Markarian 421 (Source: Cosmovision)

The high energy jets are not fully understood but are currently explained through leptonic, also called synchrotron-compton, or hadronic models. The leptonic model states that the high energy particles are emitted from the interactions of high energy electrons with synchrotron photons, the synchrotron self compton model, or from the interactions of high energy electrons with external photons, the external compton model. The hadronic model states that emission is credited to the gas cloud, ambient photons, electromagnetic field from the jet, or some different high energy particles powered by acceleration of high energy protons (Acciari, et al. 2011, Fegan 2011, Blazejowski, et al. 2005).

When one considers the correlation between x rays and gamma rays during a flare, the leptonic model is superior. However, the hadronic model is more capable of handling so called “orphan” flares (Bonnoli 2009). Overall, the leptonic model is favored for its simplicity and ability to maintain an adequate explanation of the phenomenon (Krawczynski 2007). As more research is done on gamma ray emission, the correct model for the high energy jets will become more apparent.

During the 2007/2008 observing season we observed Markarian 421 for over 30 hours and in this paper report the statistical significance of gamma ray emissions. Additionally, we correlate our results with x ray (RXTE-ASM) data.

Methods

When a gamma ray hits the Earth’s atmosphere, it produces electron-positron pairs. These pairs, in turn, cause a shower of secondary electromagnetic particles to cascade down towards the Earth. This electromagnetic cascade is called Cherenkov radiation and appears as a faint bluish glow more commonly seen in nuclear reactors. While we cannot see the gamma rays directly from Earth, Cherenkov radiation can be detected by ground based atmospheric Cherenkov imaging telescopes. These telescopes are made of large arrays of mirrors and a powerful camera composed of many photomultiplier tubes. The photomultiplier tubes pick up the faint bluish glow of the Cherenkov radiation which is reflected off of the mirror array and magnify the radiation as to allow for better resolution. Additional sensitivity is acquired from stereoscope imaging as seen in Figure 2. Stereoscope imaging comes from having multiple telescopes pointing at the same source. This allows for the Cherenkov radiation to be seen from different locations and angles making it easier to recognize the location of the source in the sky. Once Cherenkov radiation is observed, a gamma ray source can be located and then identified with an accuracy of 99.7% (Cantanese & Weekes 1999).

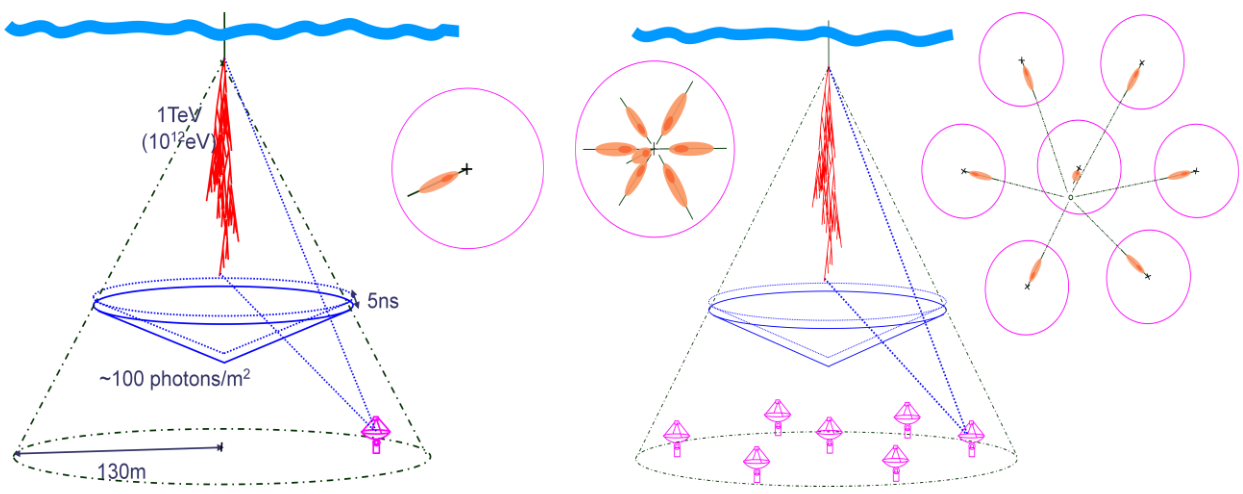

Figure 2: When a gamma ray hits the atmosphere, it turns into an electromagnetic cascade. This electromagnetic cascade is detected by the Cherenkov telescope as seen on the left. However, when there are many telescopes, as seen on the right, the image from each telescope can be composited into one image, increasing the sensitivity of the telescope and the ability to locate the source.

The observations of Markarian 421 were carried out by VERITAS. VERITAS, the Very Energetic Radiation Imaging Telescope Array System, as seen in Figure 3, is located on Mount Hopkins near Amado in Southern Arizona at an elevation of 1.3 km and latitude of 32 degrees. It has sensitivity from 10^{11} eV, 100 GeV, to greater than 10^{13} eV, around 30 TeV. VERITAS consists of an array of four ground based atmospheric Cherenkov imaging telescopes. Each has a 12 meter diameter mirror array composed of 350 mirrors and a 3.5 degree field of view camera consisting of 499 photomultiplier tubes (Holder, et al. 2006).

Figure 3: VERITAS is an array of four Cherenkov telescopes located in Southern Arizona. Each telescope has a dish of mirrors measuring 12 m and a camera composed of 499 photomultiplier tubes.

The observations of Markarian 421 were done in the 2007/2008 observing season, from November 2007 until June 2008 with 33.9 hours in total observation time. All observations were taken in wobble mode. Wobble mode is when the source is offset by 0.5 degrees. This allows the telescopes to simultaneously collect gamma ray data from the source and any events that may be coming from the background, allowing us to determine if the target is a source or appears as a source because of ambient gamma rays (Colin 2007). Usable data was then selected on the basis of weather using the trigger rate which is based upon the light threshold.

All data was analyzed by the GrISU analysis package at the University of Utah. GrISU was specifically developed for the statistical analysis of VERITAS data (Colin 2007). When this analysis was applied to four hours of Crab Nebula data taken in the same observing season, it resulted in an average of 7.7 events per minute and a statistical significance of 61.6 sigma.

Results

In observations of Markarian 421, VERITAS detected an excess of 20,380 events in the 34 hours of observation done in the direction of Markarian 421. This corresponds to a statistical significance of 235.6 sigma and an average rate of 10.0 events per minute. These results are displayed in Table 1 and Figure 4. A more detailed table of the observations of Markarian 421 which include the date, duration, excess, rate, and significance can be found in Appendix A.

On Count	21652 events
Off Count	8905 events
Excess	20379.87 events
Significance	235.69 sigma
Source Rate	10.0339 +- 0.0727 events/minute
Background Rate	0.6263 +- 0.0066 events/minute

Table 1: Data set of Markarian 421 taken in the 2007/2008 observing year which ran from November until June. During this time Markarian 421 was observed for 33.9 hours at a rate of 10.0 events per minute.

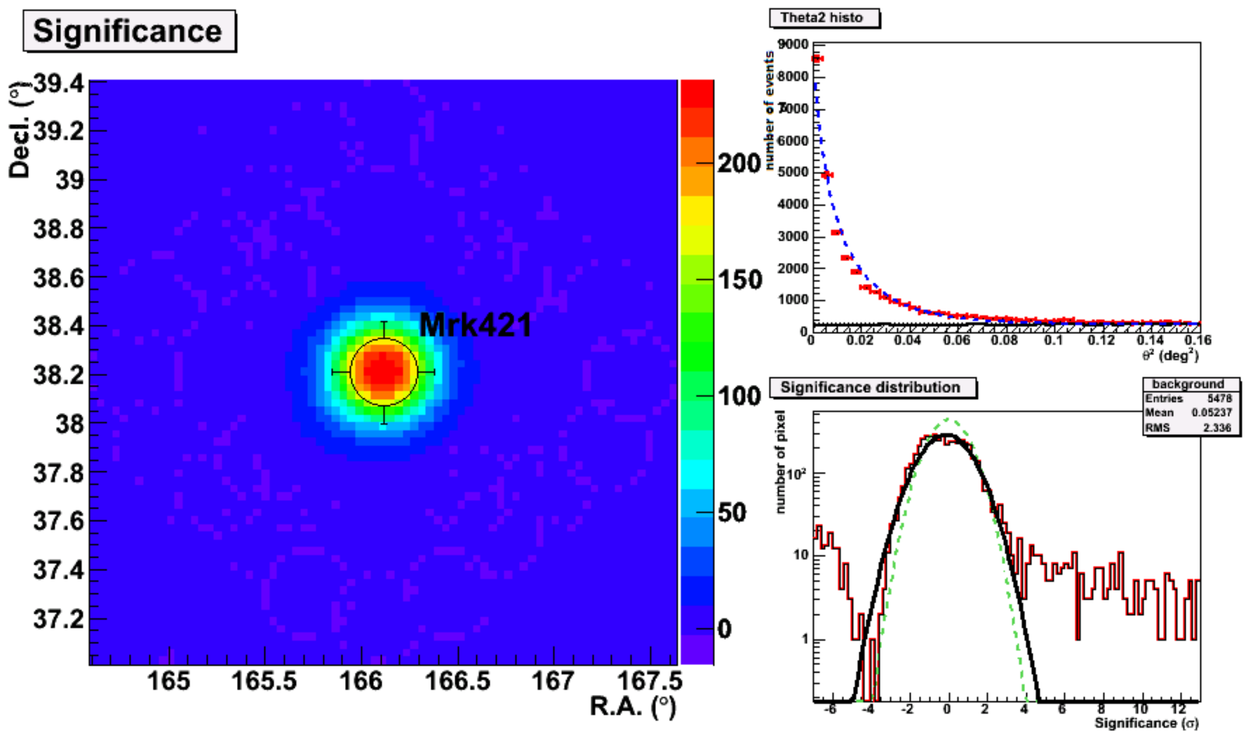

Figure 4: The significance graph on the left shows the location of Markarian 421 in the sky and its relative significance compared to its background. The purple rings around the central point indicate that the source is so strong that the background is considered to be negative. The theta squared graph on the top right compares the source, Markarian 421, to the Crab Nebula which is considered to be a point source. As the lines are almost identical, it can be concluded that Markarian 421 is, indeed, a point source like the Crab Nebula. The significance distribution graph on the bottom right is the observation data compared to a standard Gaussian curve. If the data were simply background noise, it would fit the curve perfectly. However, as the data drastically diverges from the curve, it is indicated that Markarian 421 is a point source of gamma rays.

The gamma ray observation data presented was correlated with Rossi X Ray Timing Explorer –All Sky Monitor (RXTE-ASM) data as seen in Figure 5. No apparent correlation is detected. It is speculated that the correlation between x rays and gamma rays lies in the Rossi X Ray Timing Explorer – Proportional Counter Array (RXTE-PCA) data (Acciari, et al. 2011).

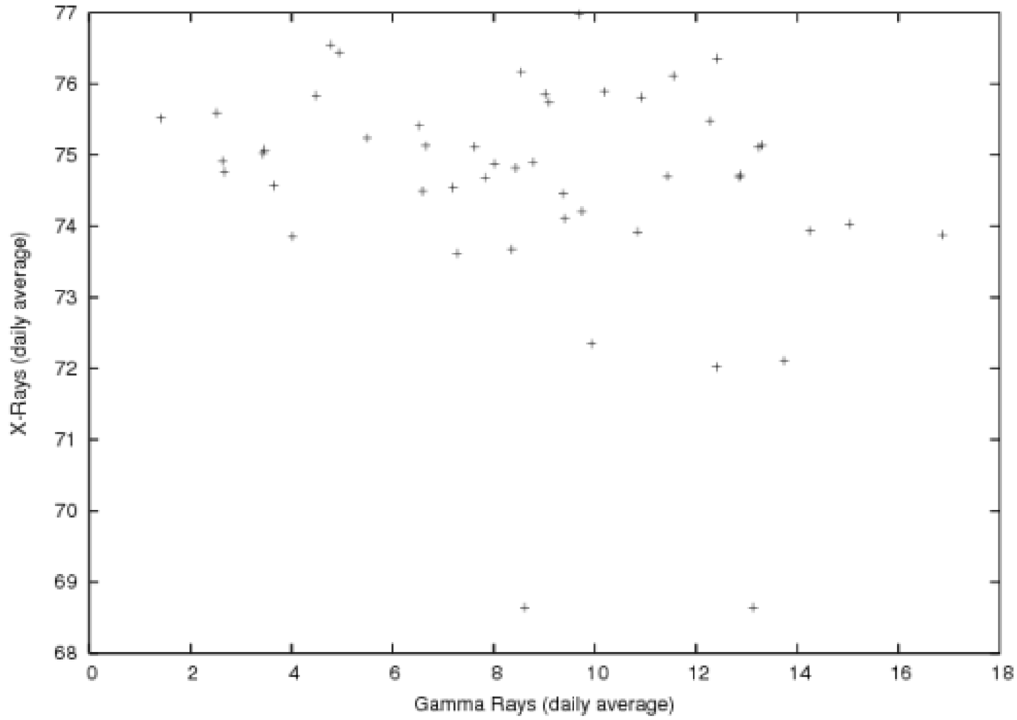

Figure 5: X ray data from RXTE-ASM versus the gamma ray data from VERITAS for the 2007/2008 observing season. Correlation between the two data sets is not apparent and it is hypothesized that the correlation will be found between the RXTE-PCA and VERITAS data.

Discussion

For the 2007/2008 observing season, Markarian 421 was seen by VERITAS at 235 sigma with 34 hours of observation. The average flux was 10.0 events per minute, compared with 7.7 events per minute for the Crab Nebula in the same observing season.

There is no strong evidence for a correlation between gamma ray data from VERITAS and x ray data from RXTE-ASM. It is suspected that the correlation lies not in the

RXTE-ASM data but in the RXTE-PCA data. The difference in correlation is that RXTE-ASM data covers energies from 2-12 keV while RXTE-PCA data covers from 2-60 keV (Acciari, et al. 2011). The increased sensitivity and wider breadth of energies found in the RXTE-PCA data would more likely result in positive correlation. Therefore, the correlation between VERITAS data and RXTE-PCA data should be investigated further.

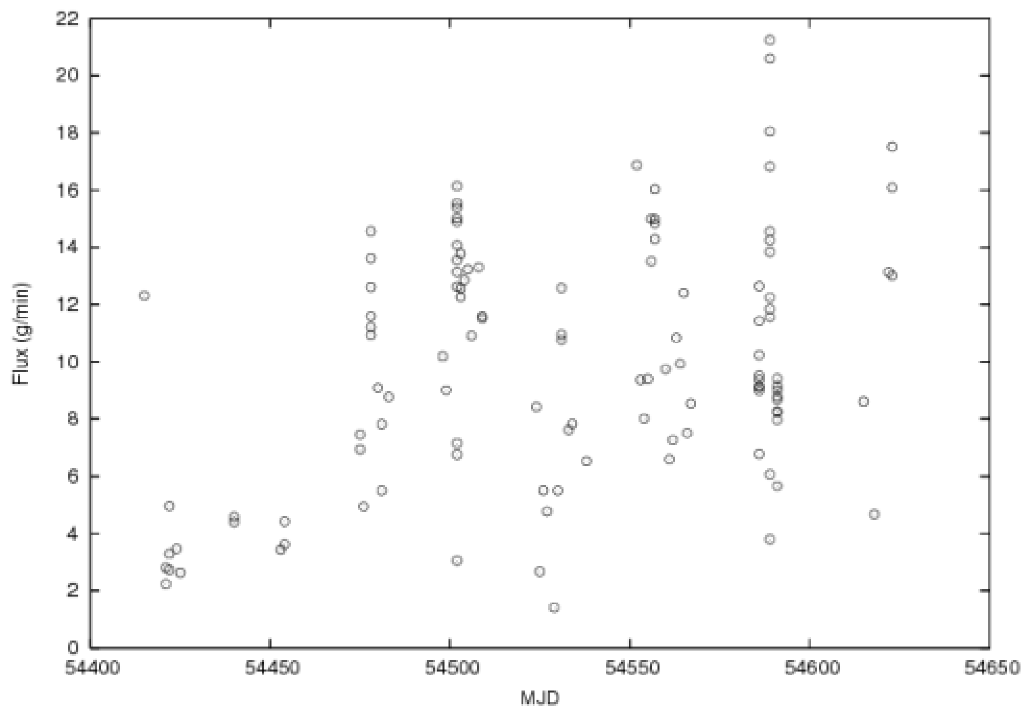

Figure 6: A significance plot of the data taken during the 2007/2008 observing season by VERITAS. The average flux for each twenty minute run is graphed against the modified Julian date enabling one to visualize the rapid fluctuations in the event rate that occurred within one night. Markarian 421 fluctuates on timescales from minutes to days and is closely monitored by many gamma ray telescopes including VERITAS because of this flaring activity.

Markarian 421 was greatly variable during this observing season making it an exciting source to monitor. At times the flaring occurred over a period of days or even months.

However, most of the flaring occurred on the time scale of minutes and hours as seen in Figure 6. This flaring greatly limits the models which are proposed to explain the high energy particle emission and implies that if the current models hold, there is significant Doppler boosting and a compact emission region associated with the high energy jets (Buckley, et al. 1996).

Through the observations of Markarian 421, its flaring episodes, and the correlation between gamma ray and x ray data, it is hoped that new emission models will be developed, or that old ones will be modified, so that we may further understand this phenomenon occurring in the galaxies which surround us.

Acknowledgements

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Appendix A: Details Table for the Target Markarian 421

Date/Run	Duration	Excess	Rate (g/min)	Significance
20071111/37847	14.0 min	172.43	12.316 +- 0.994	19.892874
20071117/38047	6.9 min	15.43	2.236 +- 0.677	4.478736
20071117/38049	16.3 min	45.71	2.805 +- 0.492	7.739719
20071118/38077	20.1 min	66	3.284 +- 0.463	10.016675
20071118/38078	20.1 min	54.86	2.729 +- 0.439	8.404032
20071118/38079	8.1 min	40.14	4.956 +- 0.885	8.028008
20071120/38112	20.1 min	69.71	3.468 +- 0.474	10.400942
20071121/38120	20.0 min	52.71	2.636 +- 0.432	8.24704
20071206/38279	20.1 min	92	4.577 +- 0.514	13.793919
20071206/38280	20.1 min	88.43	4.399 +- 0.516	12.721571
20071219/38477	20.1 min	69.14	3.440 +- 0.459	11.074705
20071220/38487	20.1 min	88.86	4.421 +- 0.545	11.271204
20071220/38488	20.0 min	72.43	3.621 +- 0.507	9.65914
20080110/38701	20.0 min	149.14	7.457 +- 0.644	18.757891
20080110/38705	25.1 min	174.29	6.944 +- 0.557	20.010889
20080111/38729	20.1 min	99.29	4.940 +- 0.536	14.189997
20080113/38806	20.1 min	225.29	11.208 +- 0.776	24.396164
20080113/38807	20.1 min	233	11.592 +- 0.783	25.578545
20080113/38808	20.0 min	291.14	14.557 +- 0.873	29.672586
20080113/38809	12.4 min	168.86	13.618 +- 1.076	22.170221
20080113/38812	20.1 min	219.86	10.938 +- 0.759	25.14698
20080113/38813	20.1 min	253.57	12.615 +- 0.811	27.662468
20080115/38864	20.1 min	182.71	9.090 +- 0.694	22.624802
20080116/38892	20.1 min	157.14	7.818 +- 0.632	22.84897
20080116/38893	20.1 min	110.43	5.494 +- 0.530	19.232832
20080118/38906	10.1 min	88.57	8.769 +- 0.964	15.576379
20080202/39049	9.8 min	99.86	10.190 +- 1.066	15.864191
20080203/39082	10.4 min	93.71	9.011 +- 0.971	15.482635
20080206/39114	20.1 min	61.43	3.056 +- 0.413	11.887956
20080206/39115	20.0 min	135.29	6.764 +- 0.603	19.119839
20080206/39116	20.1 min	143.71	7.150 +- 0.623	19.143549
20080206/39123	20.0 min	262.71	13.136 +- 0.830	28.022898
20080206/39124	20.1 min	272.43	13.554 +- 0.837	29.143118
20080206/39125	20.1 min	301.86	15.018 +- 0.879	31.10944
20080206/39126	20.0 min	252.57	12.629 +- 0.811	27.890764
20080206/39127	20.1 min	309.29	15.387 +- 0.897	30.29772
20080206/39128	20.1 min	299.29	14.890 +- 0.875	31.085779
20080206/39129	20.1 min	312.29	15.537 +- 0.898	30.997438

20080206/39130	20.1 min	324.43	16.141 +- 0.913	32.035183
20080206/39131	20.1 min	282.86	14.073 +- 0.859	28.819647
20080207/39150	20.1 min	246.29	12.253 +- 0.809	25.831461
20080207/39151	20.0 min	251.43	12.571 +- 0.819	26.439892
20080207/39160	20.1 min	276.86	13.774 +- 0.853	27.953037
20080208/39196	20.0 min	257.14	12.857 +- 0.831	26.295702
20080209/39231	20.1 min	265.86	13.227 +- 0.832	27.995361
20080210/39247	20.0 min	218.29	10.914 +- 0.763	24.619476
20080212/39309	20.1 min	267.43	13.305 +- 0.837	27.730305
20080213/39351	20.0 min	231.86	11.593 +- 0.787	25.217945
20080213/39352	20.1 min	231.43	11.514 +- 0.784	25.086039
20080228/39515	20.0 min	168.57	8.429 +- 0.680	20.453781
20080229/39529	20.0 min	53.43	2.671 +- 0.390	10.803932
20080301/39550	20.0 min	110	5.500 +- 0.561	15.40043
20080302/39570	10.0 min	47.71	4.771 +- 0.725	10.796987
20080304/39621	10.0 min	14.14	1.414 +- 0.417	4.999283
20080305/39673	20.0 min	109.86	5.493 +- 0.546	16.884453
20080306/39698	20.0 min	251.71	12.586 +- 0.812	27.580357
20080306/39699	20.0 min	219	10.950 +- 0.761	25.125366
20080306/39700	20.0 min	215.29	10.764 +- 0.760	24.156462
20080308/39763	20.0 min	152.43	7.621 +- 0.644	19.817551
20080309/39792	10.0 min	78.29	7.829 +- 0.915	14.678826
20080313/39895	10.2 min	66.57	6.527 +- 0.830	13.351999
20080327/40031	10.0 min	168.71	16.871 +- 1.331	22.443533
20080328/40042	10.0 min	93.71	9.371 +- 0.999	16.199072
20080329/40061	10.0 min	80.14	8.014 +- 0.932	14.451789
20080330/40102	10.0 min	94	9.400 +- 0.993	16.77993
20080331/40111	10.0 min	150	15.000 +- 1.257	20.976288
20080331/40118	10.0 min	135.14	13.514 +- 1.191	20.078754
20080401/40142	10.0 min	148.29	14.829 +- 1.253	20.586256
20080401/40143	20.0 min	320.57	16.029 +- 0.916	31.041193
20080401/40144	20.0 min	285.86	14.293 +- 0.867	29.007235
20080401/40146	20.0 min	299.71	14.986 +- 0.882	30.638357
20080404/40217	10.0 min	97.43	9.743 +- 1.013	16.894863
20080405/40246	10.1 min	66.57	6.591 +- 0.838	13.351878
20080406/40276	10.0 min	72.71	7.271 +- 0.894	13.412172
20080407/40300	10.2 min	110.57	10.840 +- 1.054	18.318804
20080408/40326	20.1 min	199.57	9.929 +- 0.725	23.59306
20080409/40353	20.1 min	249.29	12.402 +- 0.810	26.505028
20080410/40386	20.1 min	151	7.512 +- 0.636	19.846409
20080411/40420	20.0 min	170.86	8.543 +- 0.702	18.959072

20080430/40576	20.1 min	229.57	11.421 +- 0.777	25.487272
20080430/40577	20.1 min	205.71	10.235 +- 0.738	23.820955
20080430/40578	20.1 min	254.14	12.644 +- 0.817	26.792212
20080430/40579	20.1 min	184	9.154 +- 0.706	21.535568
20080430/40580	20.1 min	183	9.104 +- 0.708	21.026926
20080430/40581	20.0 min	179.71	8.986 +- 0.698	21.604053
20080430/40582	20.1 min	188.29	9.367 +- 0.711	22.162107
20080430/40583	20.1 min	191.43	9.524 +- 0.718	22.199476
20080430/40584	20.1 min	136.29	6.780 +- 0.606	18.639006
20080503/40672	20.0 min	237	11.850 +- 0.792	26.112265
20080503/40673	20.1 min	232.43	11.564 +- 0.780	25.911989
20080503/40674	20.1 min	246.14	12.246 +- 0.798	27.332243
20080503/40675	20.1 min	292.43	14.549 +- 0.875	29.061838
20080503/40676	20.1 min	278.14	13.838 +- 0.851	28.5956
20080503/40678	20.1 min	286.43	14.250 +- 0.860	29.735607
20080503/40679	20.1 min	427	21.244 +- 1.042	37.802982
20080503/40680	20.1 min	414	20.597 +- 1.022	38.075199
20080503/40681	20.1 min	338.14	16.823 +- 0.928	33.341656
20080503/40682	20.1 min	362.71	18.045 +- 0.957	35.583511
20080503/40683	20.1 min	121.86	6.063 +- 0.565	18.733915
20080503/40684	20.0 min	75.86	3.793 +- 0.455	13.841914
20080505/40725	20.0 min	164.71	8.236 +- 0.668	20.655283
20080505/40726	20.1 min	181.14	9.012 +- 0.692	22.342388
20080505/40727	20.1 min	184.14	9.161 +- 0.693	23.159214
20080505/40728	20.0 min	188.29	9.414 +- 0.706	23.220966
20080505/40729	20.1 min	160.14	7.967 +- 0.656	20.389082
20080505/40730	20.1 min	176.57	8.785 +- 0.685	21.828693
20080505/40731	20.1 min	166.29	8.273 +- 0.669	20.676275
20080505/40732	20.1 min	174.29	8.671 +- 0.677	22.125071
20080505/40734	20.1 min	113.86	5.665 +- 0.560	16.439411
20080529/40970	11.8 min	101.57	8.608 +- 0.884	16.607309
20080601/41042	10.0 min	46.71	4.671 +- 0.734	9.926585
20080605/41136	10.0 min	131.29	13.129 +- 1.174	19.780724
20080606/41159	10.0 min	175.14	17.514 +- 1.357	22.769304
20080606/41160	10.0 min	160.86	16.086 +- 1.291	22.597548
20080606/41161	10.0 min	130	13.000 +- 1.170	19.553038

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