Every Datapoint Counts: Stellar Flares as a Case Study of Atmosphere-Aided Studies of Transients in the Rubin LSST Era

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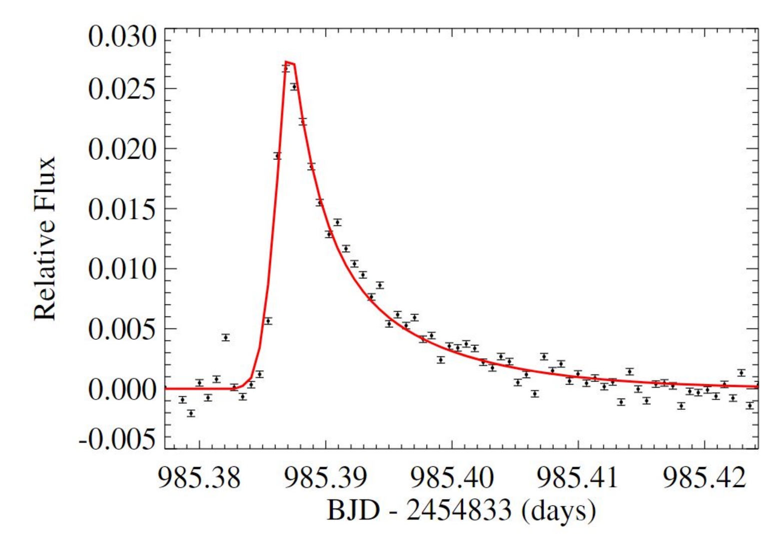
Abstract

Due to their short timescale, stellar flares are a challenging target for the most modern synoptic sky surveys. The upcoming Vera C. Rubin Legacy Survey of Space and Time (LSST), a project designed to collect more data than any precursor survey, is unlikely to detect flares with more than one data point in its main survey. We developed a methodology to enable LSST studies of stellar flares, with a focus on flare temperature and temperature evolution, which remain poorly constrained compared to flare morphology. By leveraging the sensitivity expected from the Rubin system, Differential Chromatic Refraction can be used to constrain flare temperature from a single-epoch detection, which will enable statistical studies of flare temperatures and constrain models of the physical processes behind flare emission using the unprecedentedly high volume of data produced by Rubin over the 10-year LSST. We model the refraction effect as a function of the atmospheric column density, photometric filter, and temperature of the flare, and show that flare temperatures at or above ~4,000*K* can be constrained by a single *g*-band observation at airmass $X \gtrsim 1.2$, given the minimum specified requirement on single-visit relative astrometric accuracy of LSST, and that a surprisingly large number of LSST observations is in fact likely be conducted at $X \gtrsim 1.2$, in spite of image quality requirements pushing the survey to preferentially low *X*. Having failed to measure flare DCR in LSST precursor surveys, we make recommendations on survey design and data products that enable these studies in LSST and other future surveys.

Stellar Flares

What are stellar flares?

Flares are stochastic, short-lived brightening events that occur on stellar photospheres as a result of the reconnection of magnetic field lines, and are most common in low mass stars, such as M-Dwarfs [1]. Due to their short timescale (see figure to right), Rubin is unlikely to detect flares with more than one datapoint in its main survey (LSST Wide Fast Deep). However, with the exquisite image quality and sensitivity expected from the 3.2 gigapixel LSST camera, a phenomenon known as Differential Chromatic Refraction (DCR) can be leveraged to constrain flare temperature from a single-point detection.



Above: Part of Figure 6 from [1]. Photometry of a flare measured by the *Kepler* Space Telescope, fit with a classical flare template as described in [1]. The entire plot spans only 1 hour. Within 1 hour, the LSST Wide Fast Deep survey will typically perform 1 to 2 observations.

Methodology

The angular dispersion due to DCR is calculated in steps (1)-(4) below, as described in [4]:

- λ_{eff} = effective wavelength (μm)
- S_j = transmission function
- f_λ = spectral flux (W m^{-2} μm^{-1})
- n = index of refraction
- Z = zenith angle (deg)
- Airmass = 1/cos(Z)
- R = angular deflection (arcseconds)

$$(1)\ \lambda_{eff} = \frac{\int_0^\infty f_\lambda S_j(\lambda) ln(\lambda) d\lambda}{\int_0^\infty f_\lambda S_j(\lambda) d\lambda}$$

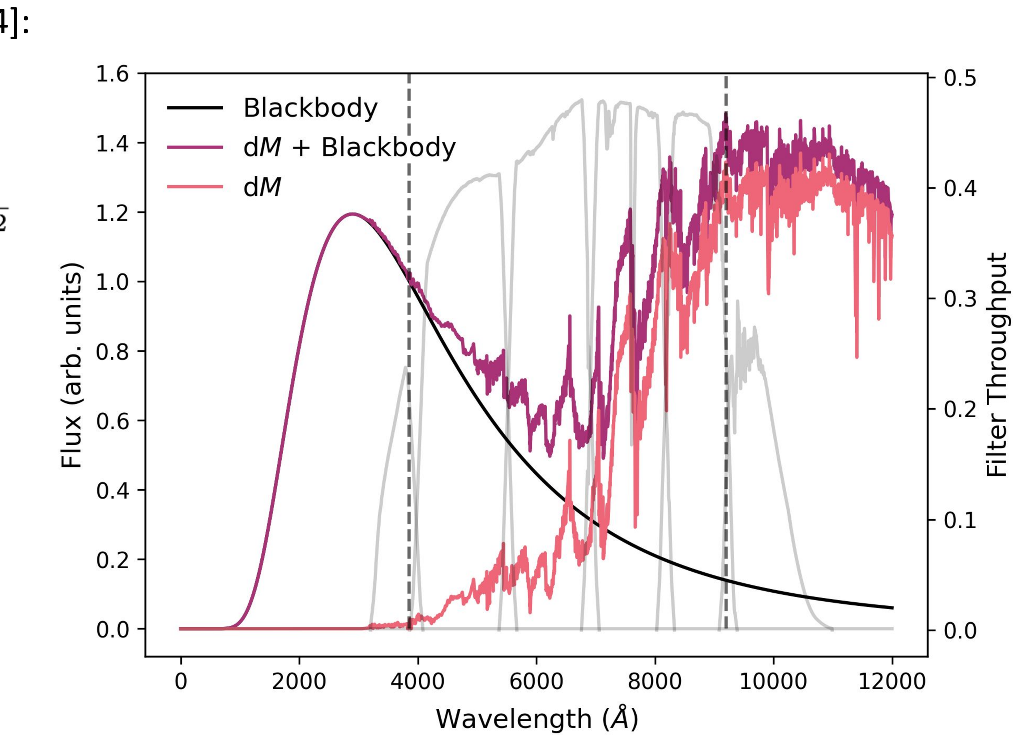
$$(2)\ [n(\lambda)-1]10^6 = 64.328 + \frac{29498.1}{146-(1/\lambda_{eff})^2} + \frac{255.4}{41-(1/\lambda_{eff})^2}$$

$$(3)\ R_0 = \frac{n^2-1}{2n^2}$$

$$(4)\ R = R_0 \tan(Z)$$

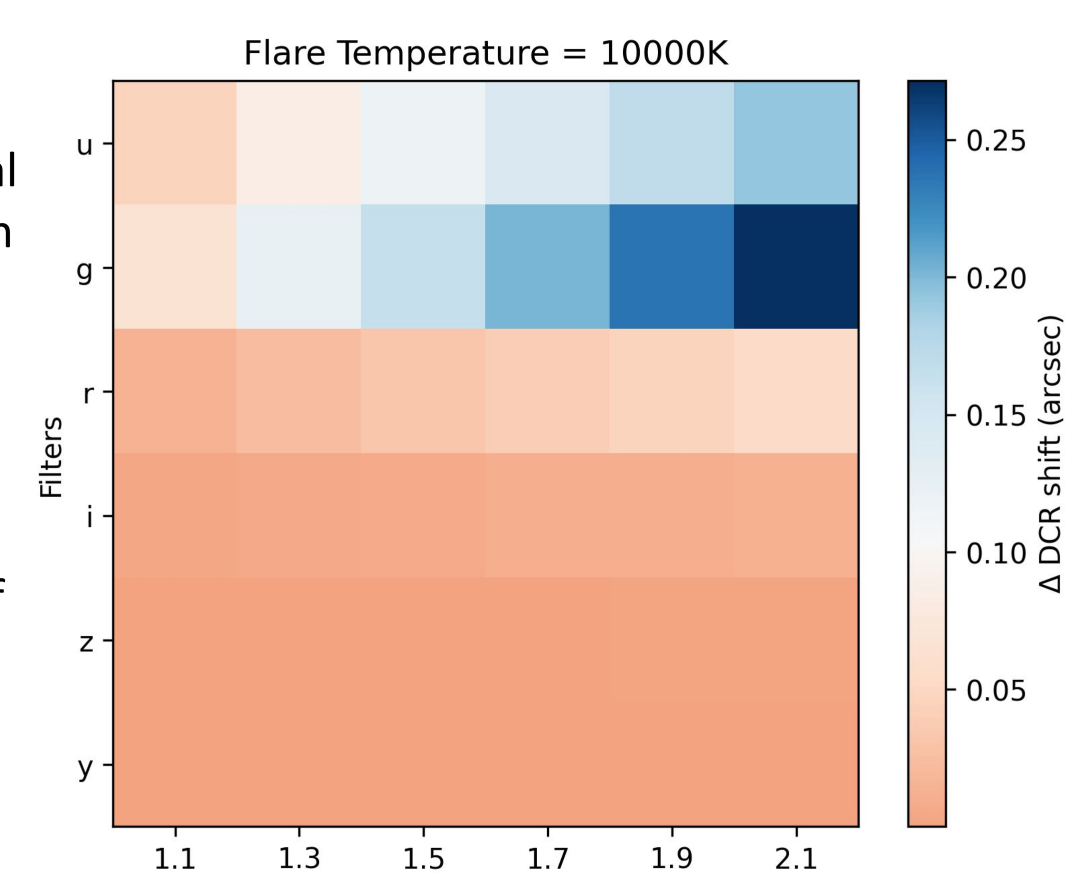
How do we simulate flares at different temperatures?

Top Right: M5 dwarf spectrum (pink) and 10000*K* blackbody spectrum (black). Sum of the pink and black spectra (purple), representing the spectrum of the M dwarf during the flare event. The blackbody and M dwarf spectra contain the same total energy over the 3,850-9,200Å range, indicated by the dashed black lines. In the background, the LSST *ugrizy* filter transmission curves are shown in grey. The ΔDCR is proportional to the change in slope of the spectrum across the filter between quiescence and flare.

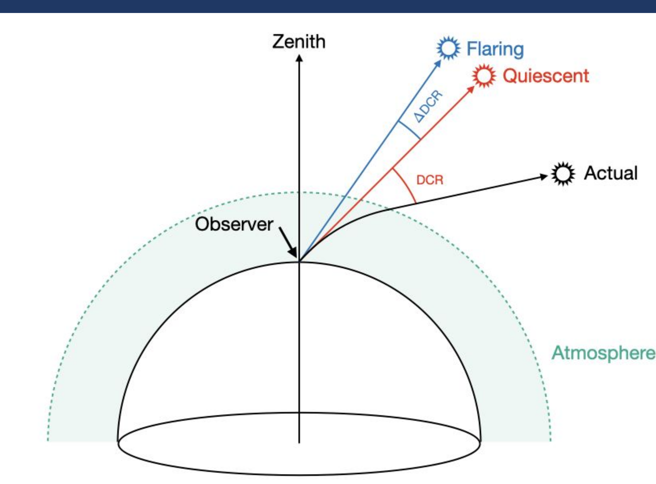


Can Rubin measure the ΔDCR from a flare?

Bottom Right: Expected magnitude of the ΔDCR effect for a flare SED approximated by a 10,000*K* blackbody as a function of airmass and filter. Blue coloring corresponds to a ΔDCR shift detectable by Rubin, and red coloring corresponds to an undetectable shift, given the astrometric accuracy goal of 0.1 arcsec. A 10,000*K* flare's ΔDCR should be detectable in *g*-band even at moderate airmasses.



Differential Chromatic Refraction



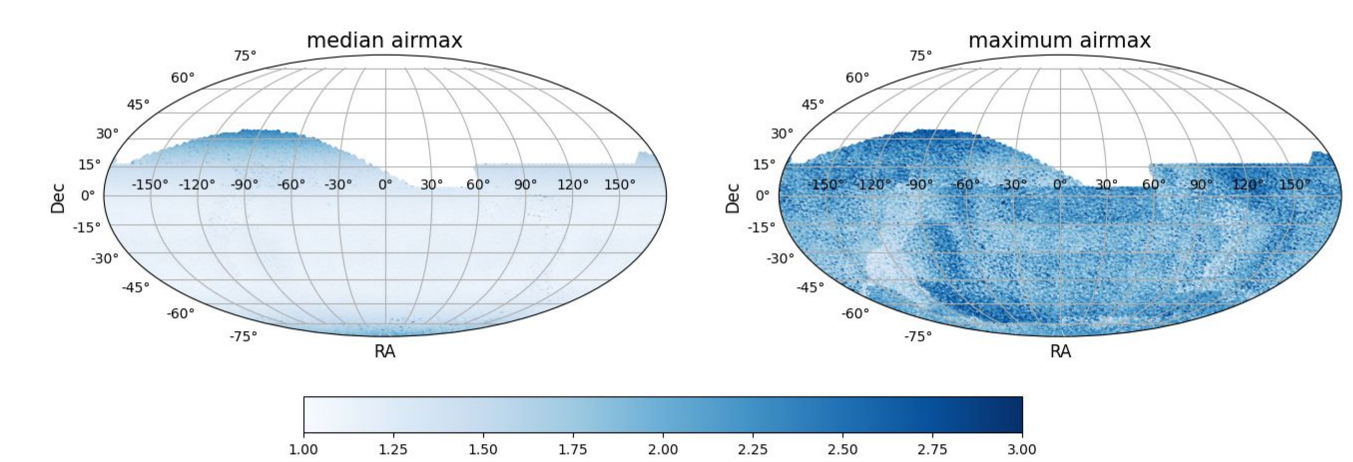
What is Differential Chromatic Refraction (DCR)?

Left: Light incident from a star is deflected by the atmosphere. The amount of deflection depends on the color (*i.e.* temperature) of the star and the amount of atmosphere the light passes through, which is called *airmass*. The chromatic change during a flare event should produce an excess in the normal DCR at quiescence, labeled as ΔDCR in the figure.

Flare Studies with Rubin

Will LSST WFD observe at sufficiently high airmasses to take advantage of DCR?

Yes! While only a fraction of overall observations, a significant number of high airmass visits are nonetheless expected.



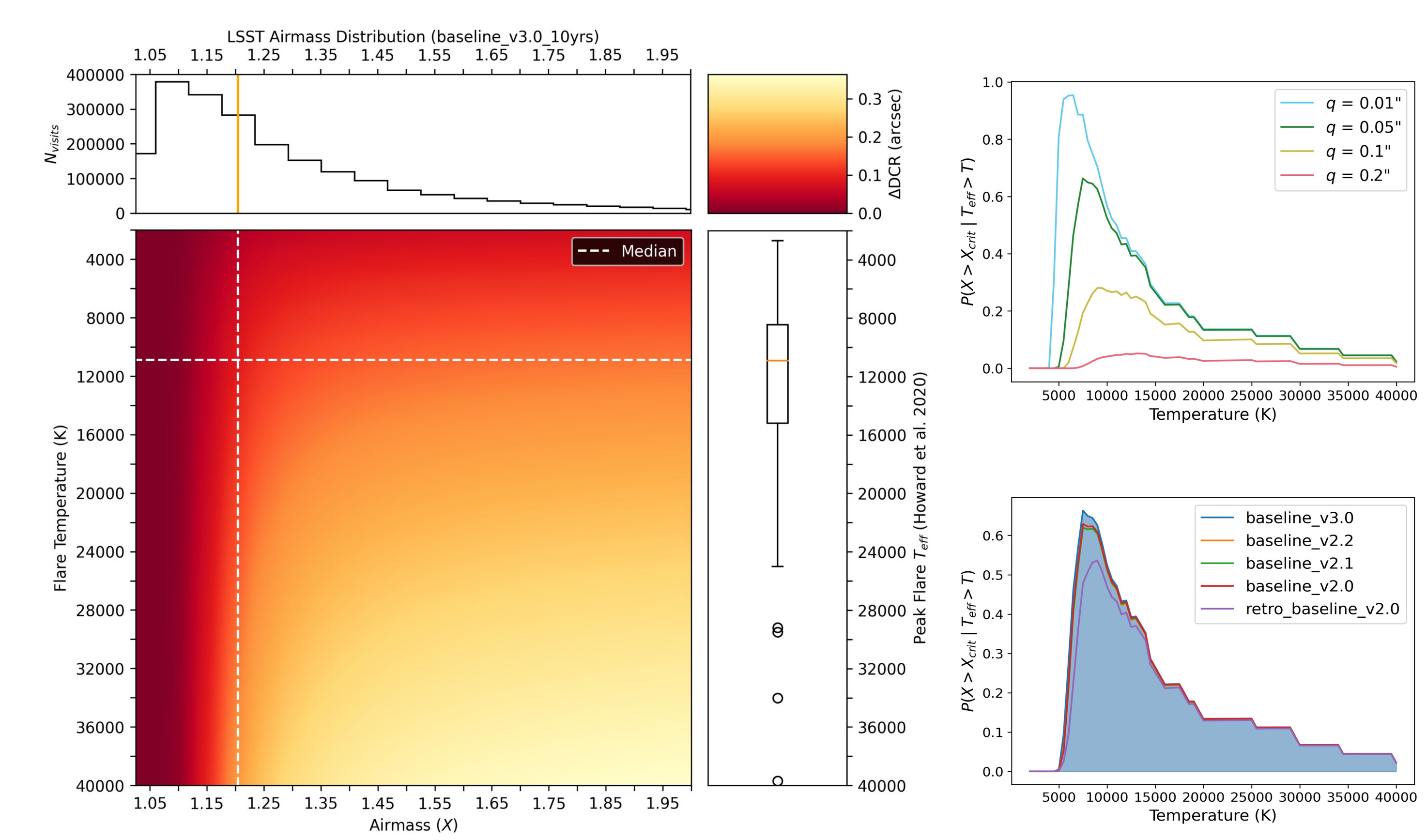
Top: Airmass sky distribution of the current LSST survey strategy proposal (baseline_v3.0_10yrs). Skymaps are shown for the median airmass (*left*) and maximum airmass (*right*) in *g*-band [2, 3].

What technical requirements will maximize our capability to measure flare temperatures with ΔDCR?

Left: ΔDCR induced as a function of flare temperature and airmass in LSST *g*-band. *Right panel:* Box-and-whiskers plot of peak effective flare temperatures measured by [5]. *Top panel:* Histogram of the per-visit airmass in the current LSST baseline observing strategy [2,3]. The median airmass and temperature are indicated by orange lines.

Top Right: Probability of detecting ΔDCR induced by a flare at or above peak effective temperature T for four different astrometric accuracy limits. The probability of DCR detection is measured as the conditional probability $P(X > X_{crit} | T_{eff} > T)$ where $X_{crit}(T,q)$ is the minimum airmass necessary for a flare of temperature *T* to produce a ΔDCR greater than the astrometric accuracy *q* and the temperature distribution of flares follows [5].

Bottom Right: Same as top right but fixing *q* = 0.05" and for five different simulations of the LSST.



References

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