Diagnosing the Clumpy Protoplanetary Disk of the UXor Type Young Star GM Cephei

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Outline

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   - Period of major flux drops
   - Rotational modulation
   - Duration and depth of flux drop events
   - Color variations
   - Polarization
   - Flux from star and envelope
3. Summary

1. Introduction

Variability of Young Star

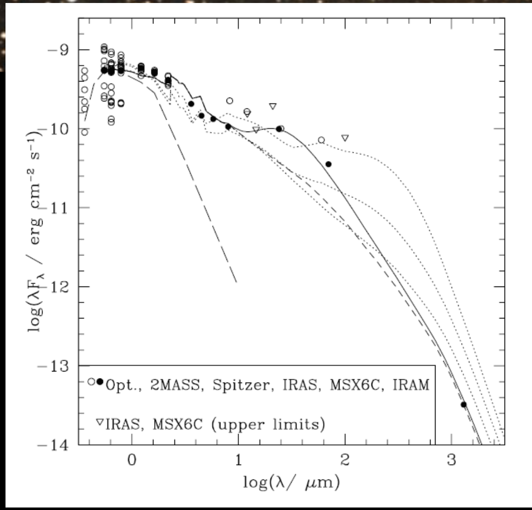
- Young Stellar Objects (YSOs)
  1. FU Ori (FUors): outburst → varying mass accretion, up to 6 mag, slow decline
  2. EX Lup (EXors) outburst → varying mass accretion, up to 5 mag, recurrent

- Sunlike Pre-Main Sequence stars (PMS)
  1. Cool spots (magnetic/chromospheric)
  2. Hot spots (accretion/shocking)

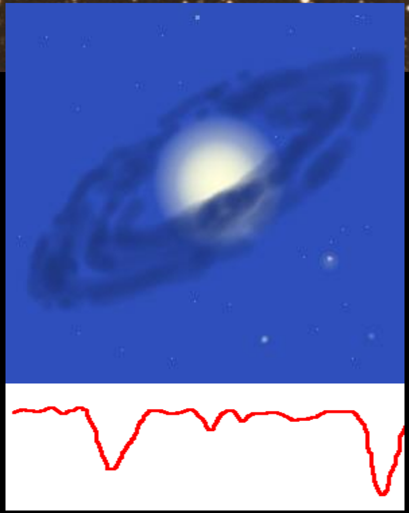
- UX Ori (UXors): circumstellar dust extinction

→ GM Cep is such a UX Ori type star

GM Cep



(Sicilia-Aquilar et al. 2008)



Credit by Prof. Pandey

- Member of Trumpler 37 (~ 1-4 Myr) (Marschall et al. 1990; Patel et al. 1995; Sicilia-Aguilar et al. 2005)
- H-alpha emission (Sicilia-Aguilar et al. 2008)
- Infrared excess (Sicilia-Aguilar et al. 2008)
- X-ray emission (Mercer et al. 2009)
- ~870 pc (Contreras et. al. 2002),
  ~830 pc (Gaia team 2018)
- F9 (Huang et al. 2013)
  G7V - K0V (Sicilia-Aguilar et al. 2008)
- v sin$i$ = 43.2 km/s
  > avg. v sin$i$ = 10.2 km/s (other members) (Sicilia-Aguilar et al. 2008)

Research history

- 2008, Sicilia-Aguilar et al. regarded GM Cep as a EX Ori type star
  → incomplete sampling
- 2010, Xiao et al. classified the star as a UX Ori candidate
  → century-long light curve from archival photographic plates
- 2012, UX Ori type was confirmed by Chen et al. 2012 and Semkov & Peneva 2012
- 2012, Chen et al. speculated on a possible recurrent time of ~ 1 year
  → based on a few major flux drop events
- 2015, Semkov et al. claimed that the star does not have period

Data sources and observations

- Literature: Sicilia-Aguilar et al. 2008; Morgenroth 1939; Suyarkova 1975; Kun (1986); Monet et al. 2003; Xiao et al. 2010; Chen et al. 2012; Semkov & Peneva 2012; Semkov et al. 2015
- Observations:

Table 1. Parameters of Telescopes

Observatory/Telescope	CCD Type	Size (pixels)	Pixel Size (μm)	FOV (arcmin^2)	RON (e^-)	# Nights
YETI Telescopes						
0.4 m SLT (Lulin)	E2V 42-40	2048×2048	13.5	30.0×30.0	7	541
0.81 m TenagraII (Tenagra)	SITe SI-03xA	1024×1024	24	14.8×14.8	29	463
0.25 m CTK-II (Jena)[a]	E2V PI47-10	1056×1027	13	21.0×20.4	7	104
0.6 m STK (Jena)[b]	E2V 42-10	2048×2048	13.5	52.8×52.8	8	79
1.0 m LOT (Lulin)	Apogee U42	2048×2048	13.5	11.0×11.0	12	48
0.61 m RC (Van de camp)	Apogee U16M	4096×4096	9	26.0×26.0	7	13
0.6 m Zeiss 600/7500 (Stara Lesna)	FLI ML 3041	2048×2048	15	14.0×14.0	5	11
Other Telescopes						
1.6 m Pirka (Nayoro)[d]	EMCCD C9100-13	512×512	16	3.3×3.3	13	133
1.5 m AZT-22 (Maidanak)	SI 600 Series	4096×4096	15	16.0×16.0	5	120
1.0 m NOWT (XinJiang)	E2V 203-82	4096×4096	12	78.0×78.0	5	108
1.2 m T1T (Michael Adrian)	SBIG STL-6303	3072×2048	9	10.0×6.7	15	12
0.51 m CDK (Mayhill)	FLI ProLine PL11002M	4008×2072	9	36.2×54.3	9	12
1.0 m ESA's OGS (Teide)[c]	Roper Spec Camera	2048×2048	13.5	13.76×13.76	8	10
1.5 m P60 (Palomar)	AR-Coated Tektronix	2048×2048	24	11.0×11.0	9	7
0.35 m ACT-452 (MAO)	QSI 516	1552×1032	9	37.6×25.0	15	2

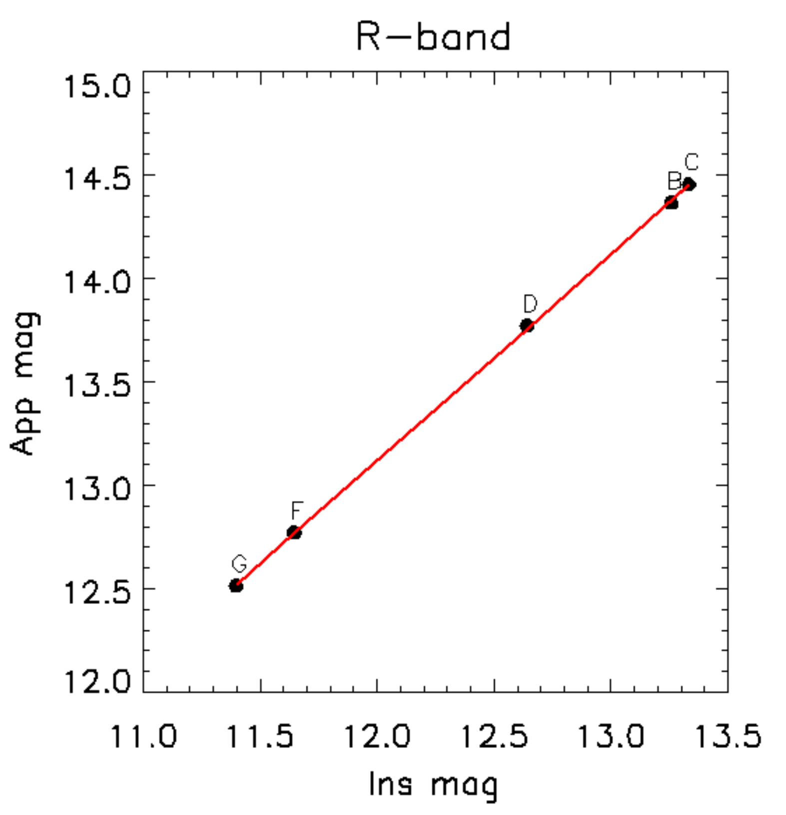
NOTE— [a]Mugrauer (2016); [b]Mugrauer & Berthold (2010); [c]Schulz et al. (2014); [d]Nayoro observatory equips EMCCD camera with their Multi-Spectral Imager (MSI) instrument (Watanabe et al. 2012).

Data sources and observations

- Data reduction: bias, dark, flat field correction
- Photometry: IDL (aper.pro) which is similar to the “IRAF/Daophot”
- Calibration: 5 reference stars from Xiao et al. 2010

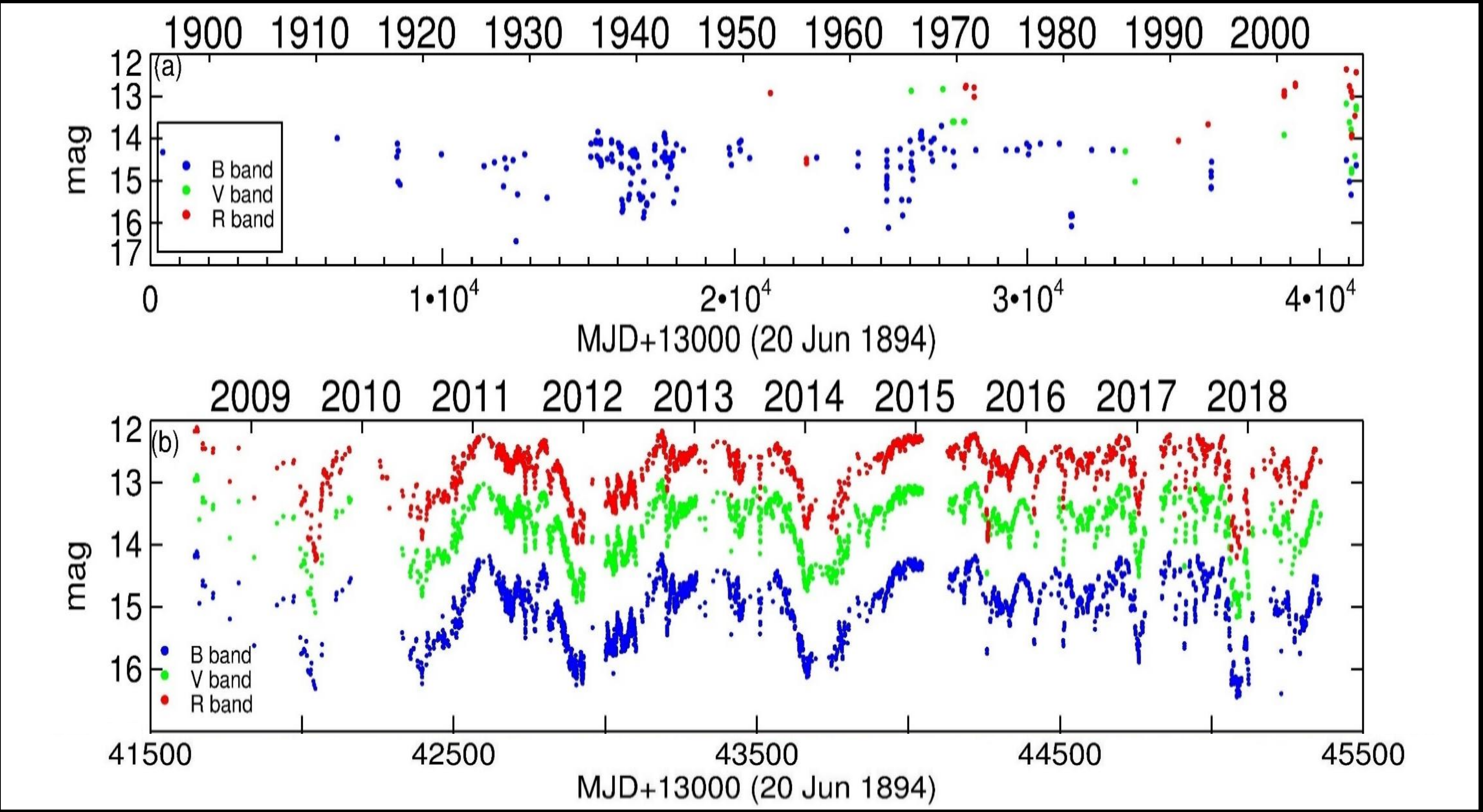
Table 2. Photometric reference stars adopted from Xiao et al. (2010)

Ref. Star	R.A. (J2000) [deg]	Dec. (J2000) [deg]	B [mag]	V [mag]	R [mag]
Star B	324.529226	57.508117	16.015	14.961	14.364
Star C	324.563184	57.492816	15.445	14.837	14.455
Star D	324.543391	57.505287	15.333	14.357	13.770
Star F	324.586443	57.487231	14.389	13.358	12.770
Star G	324.600939	57.556202	13.374	12.829	12.513



2. Results

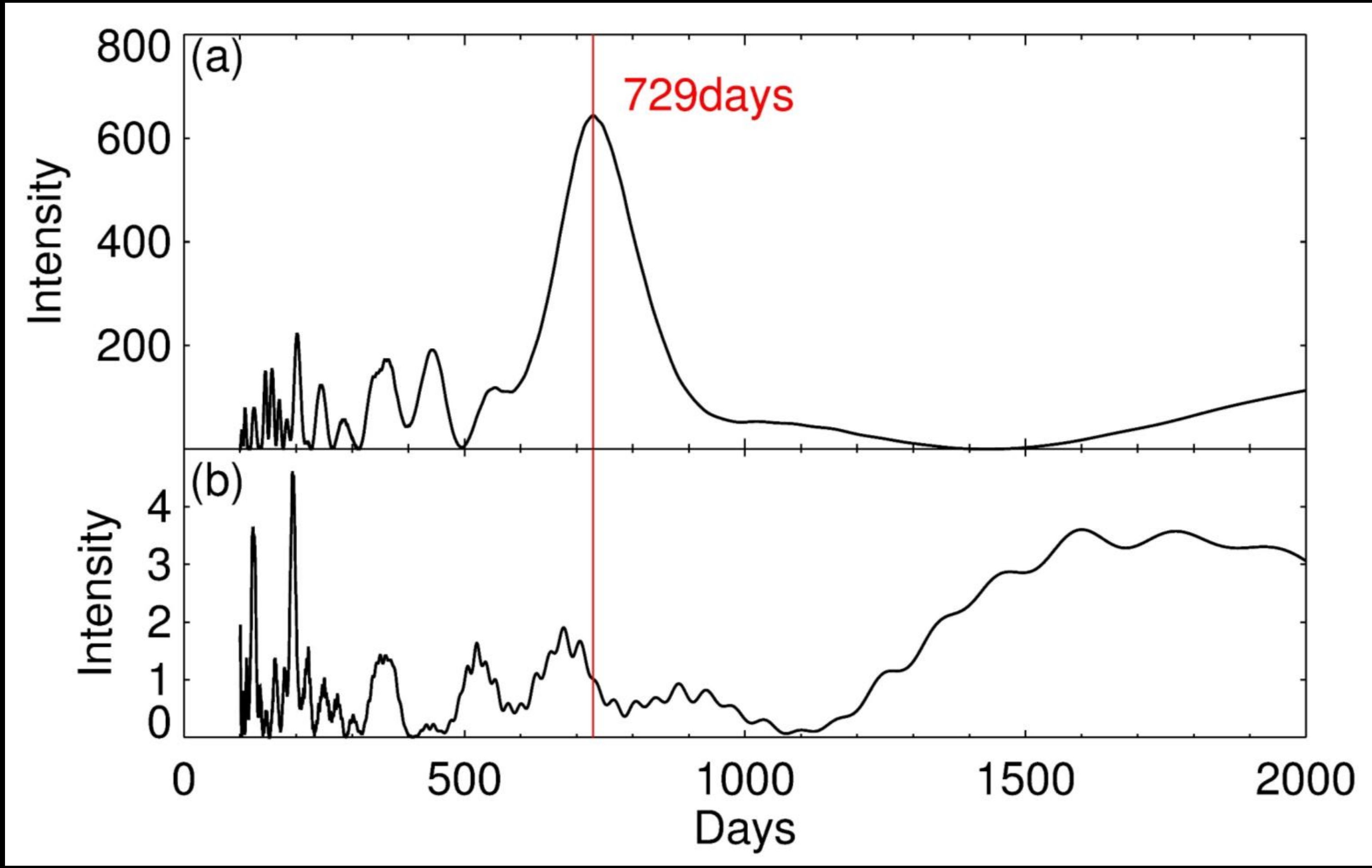
Photometric Variations



Three kinds of variations:

1. Major flux drops
   - ~ 1.0 — 2.5 mag
   - months
2. Minor flux drops
   - ~ 0.2 — 1.0 mag
   - days to weeks
3. Rotational modulation
   - ~ 0.05 mag
   - a few days

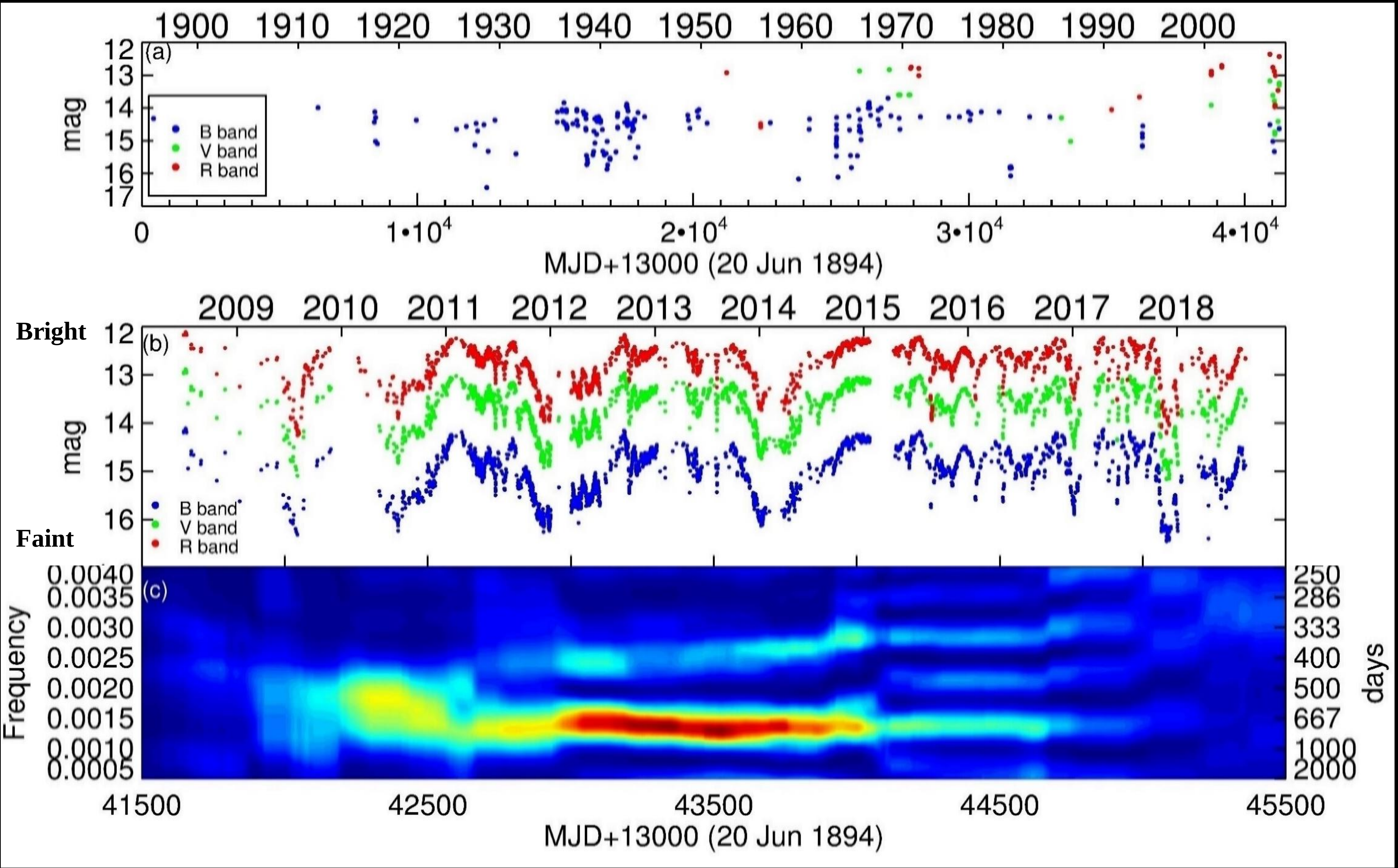
Period of major flux drops



- UXors are thought to be irregular
- Lomb-Scargle algorithm
- Peak at ~730 days
  → recurrent dip minima in the light curve

- Sampling function peak at ~ 360 days
  → annual observing gap

Period of major flux drops



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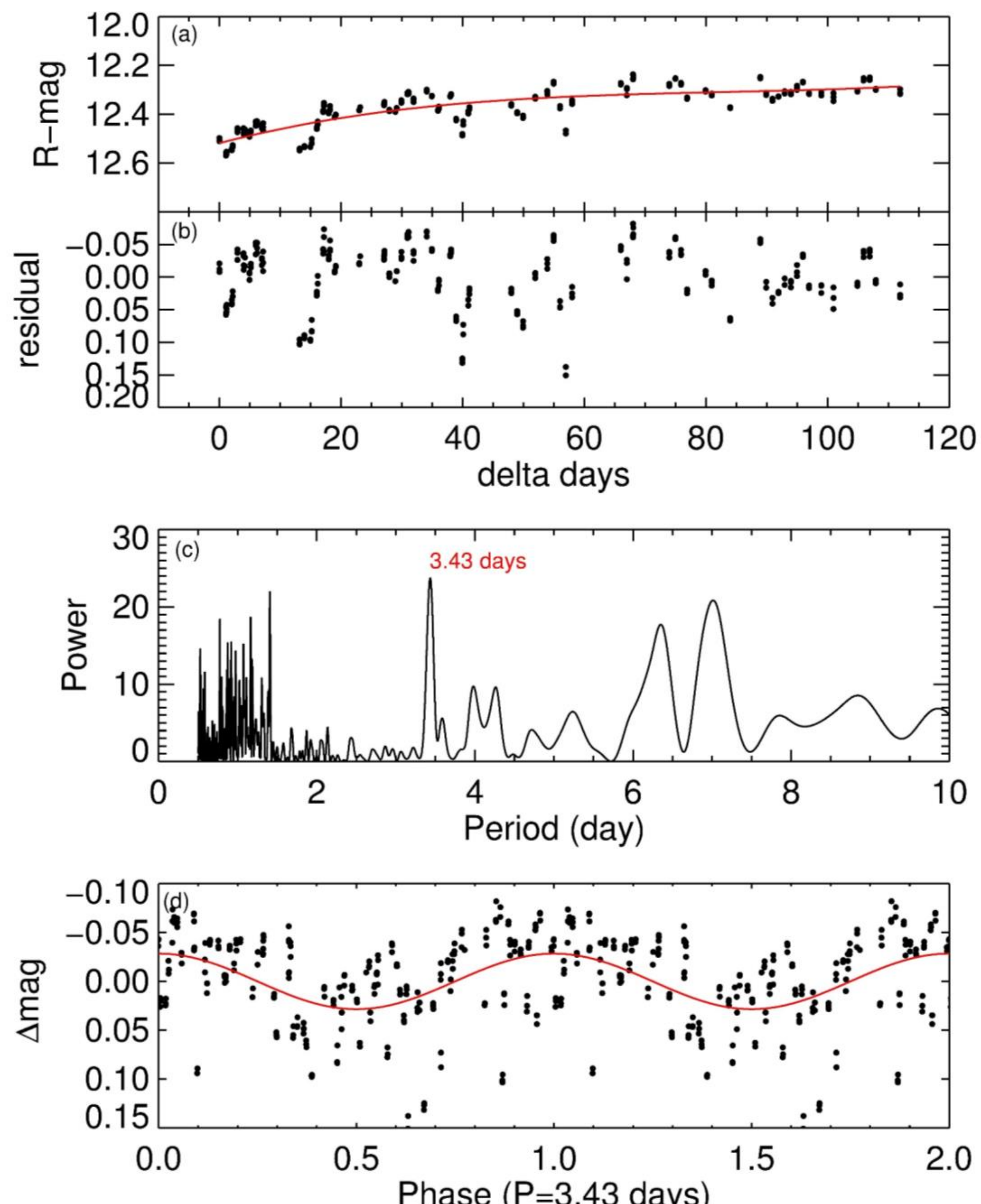
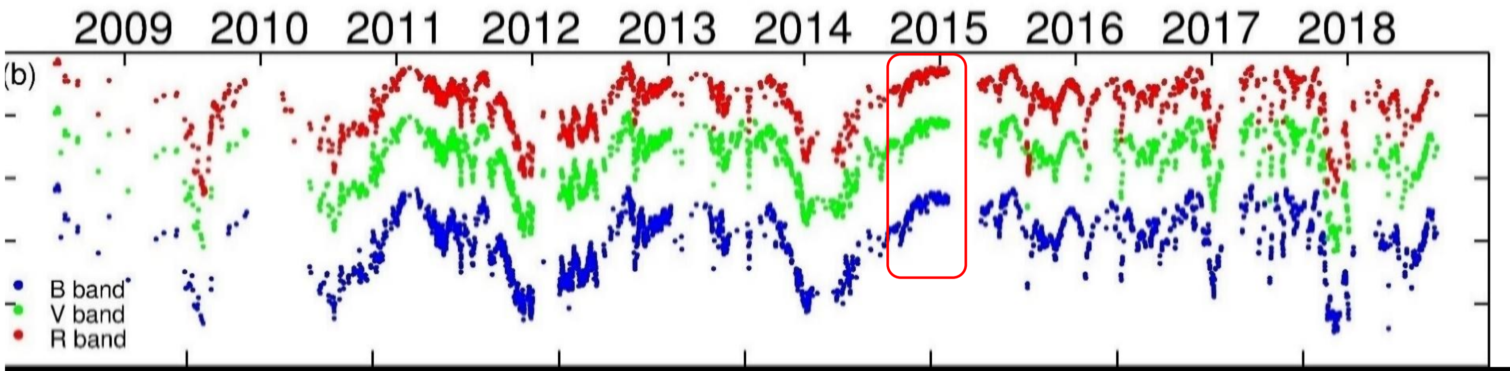
Dynamical period analysis

- Repetitive L-S
- Window 2000 days
- Step of one day
- Peak ~ 700 days

→ from prominent min.

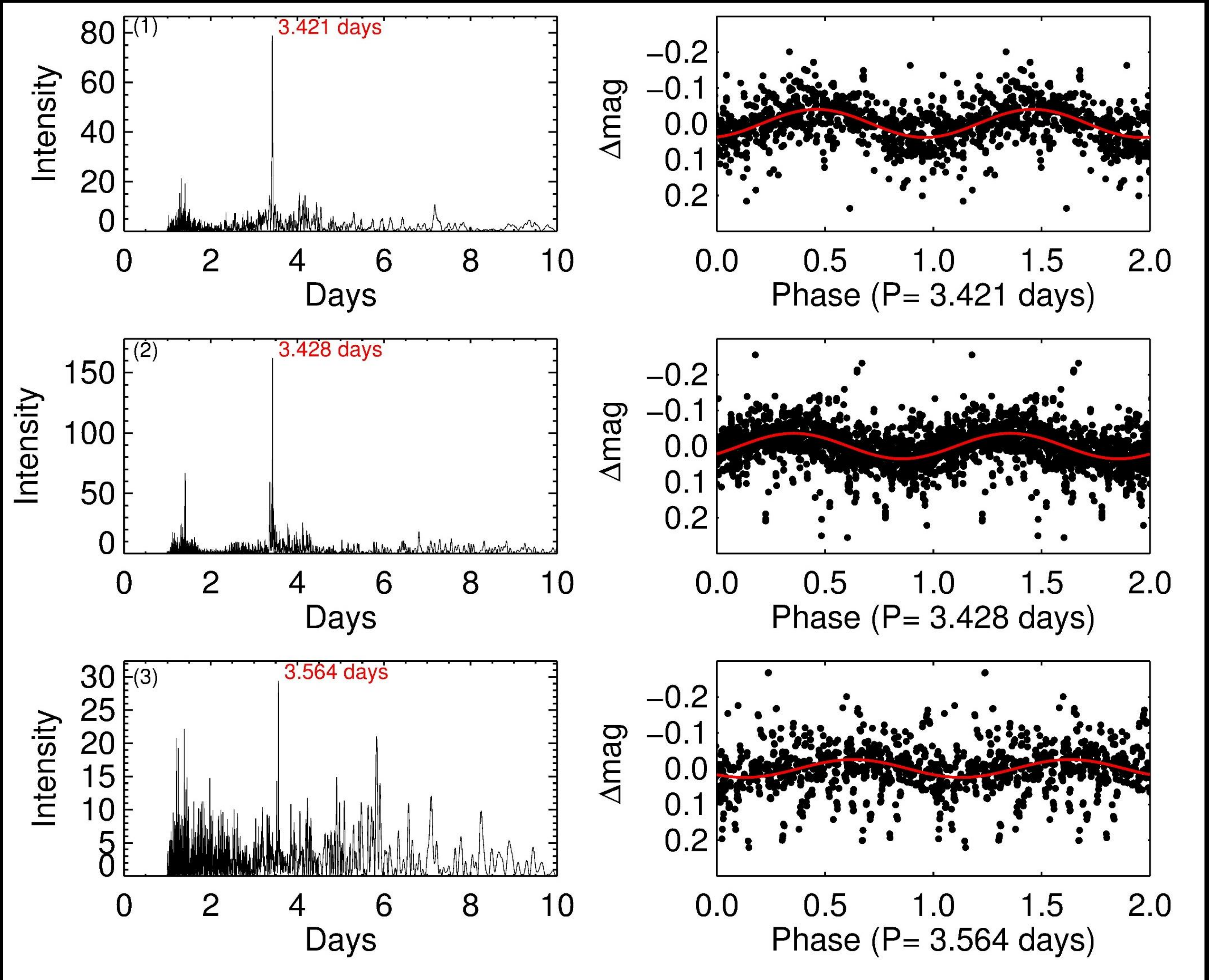
Rotational modulation





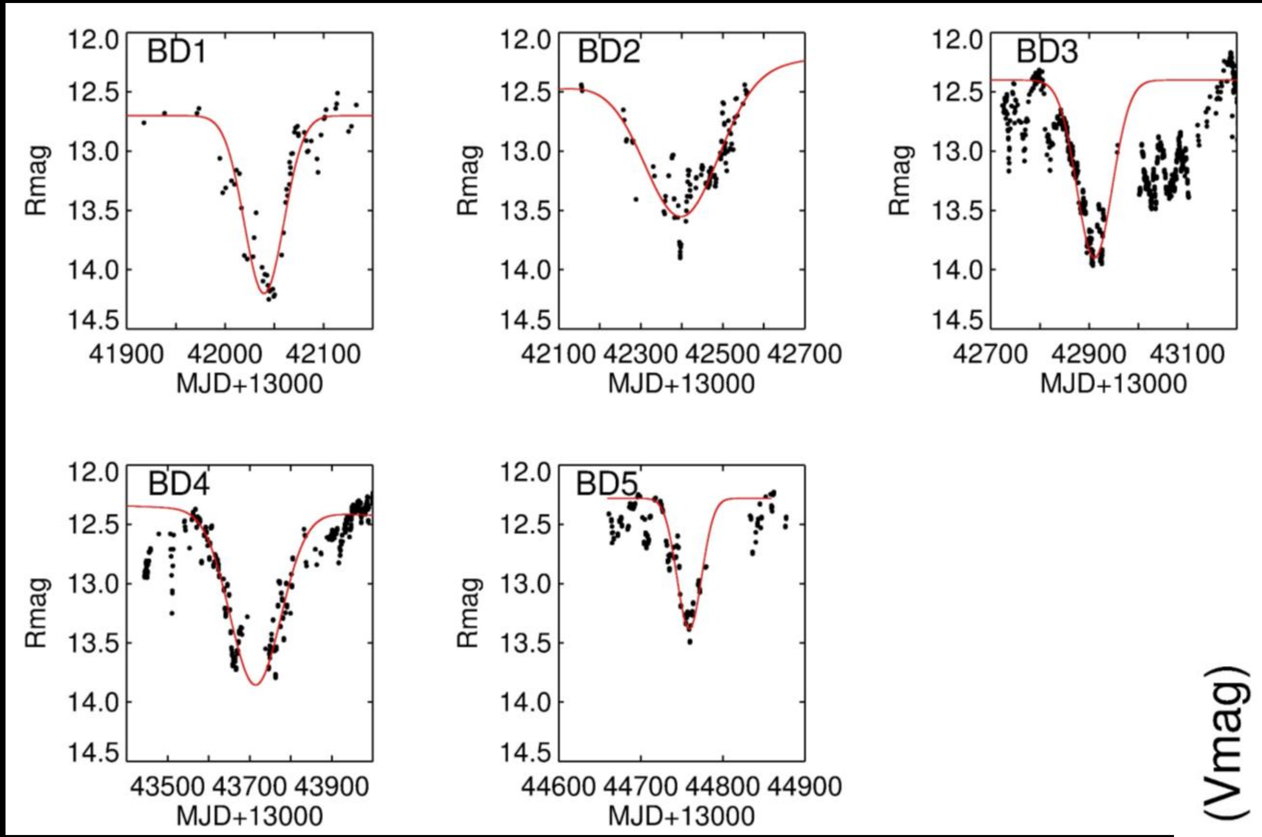
- Segment of mid-2014 to end of 2014
  → bright state → less influence by major flux drops
- Third-order polynomial fitting
  → removed slow-varying trend
- Lomb-Scargle analysis
  → peak at ~3.43 days stands out
- Folded light curve with best fitting
  → caused by modulation of cool spots
- Expected rotational period of GM Cep is ~ 3 — 6 d from $v \sin i$ ~ 43.2 km/s and 3-6 $R_{\odot}$ (Sicilia-Aguilar et al. 2008)

Rotational modulation



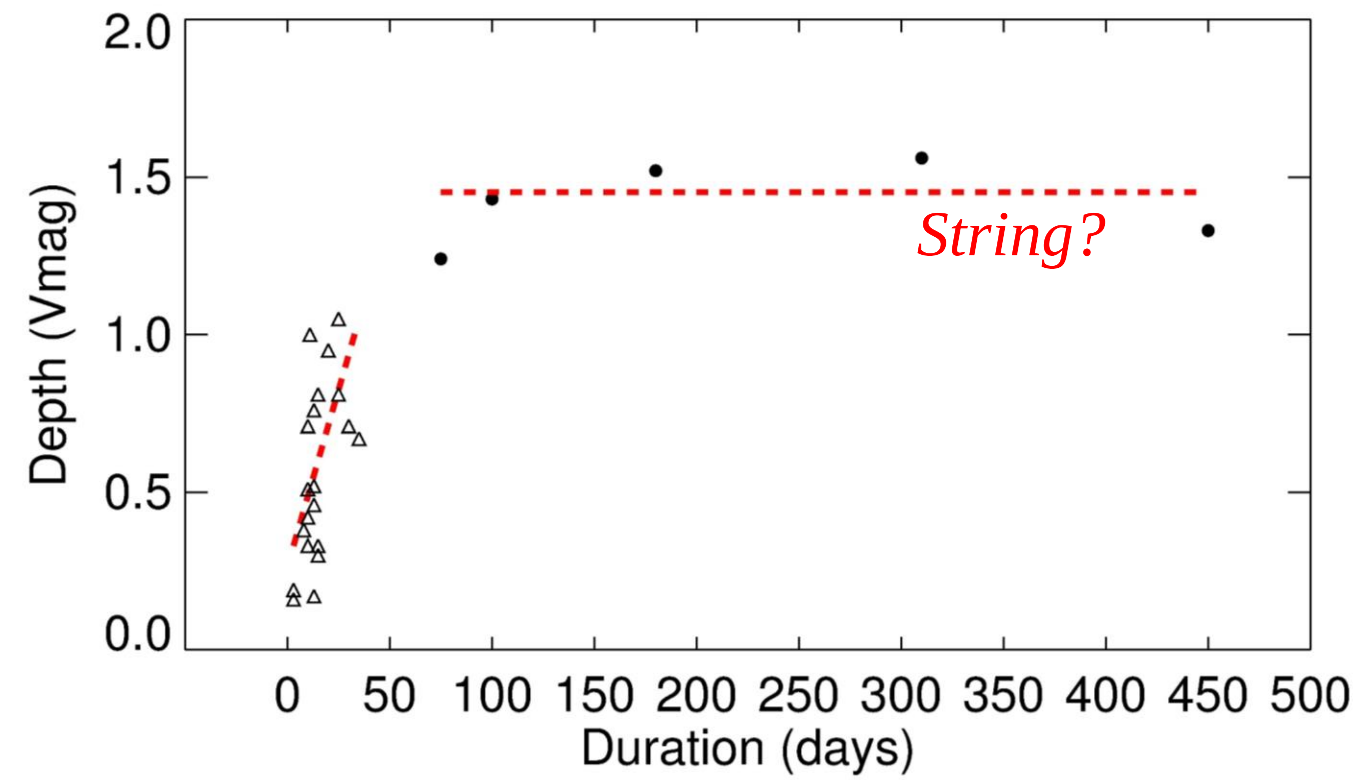
- Detrended mechanism
  → smooth with 8-d window
  → removed low-freq. signal > ~10 days
- Three segments
  1. 41500 – 43000
     $P_1 = 3.421\ d, A_1 = 0.039\ mag$
  2. 43000 – 44250
     $P_2 = 3.428\ d, A_2 = 0.036\ mag$
  3. 44250 – 45500
     $P_3 = 3.564\ d, A_3 = 0.025\ mag$
- Scattering is intrinsic variation
  e.g. differing total spots area
- Period ↑ with Amplitude ↓
  → opposite Schwabe cycle?

Duration and Depth

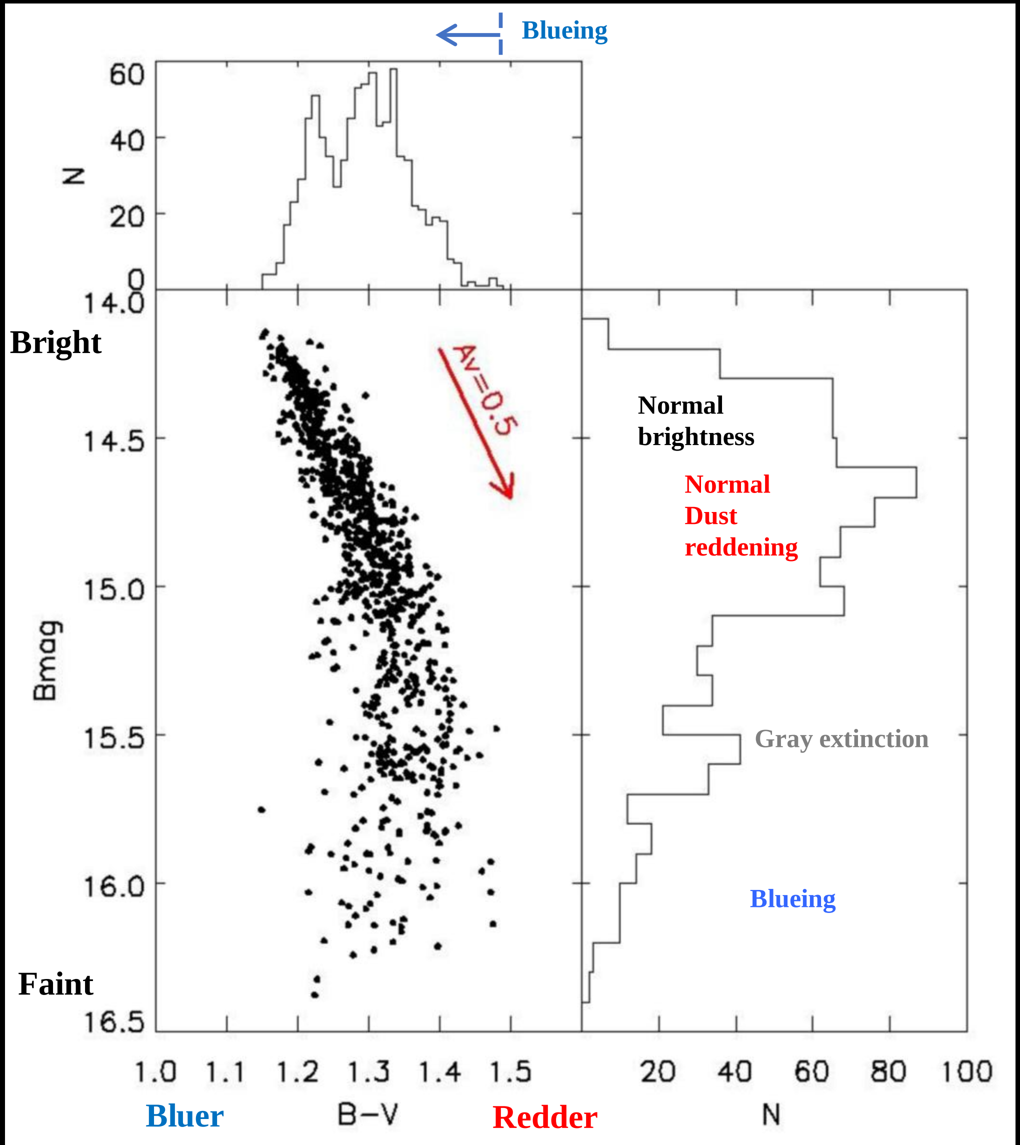


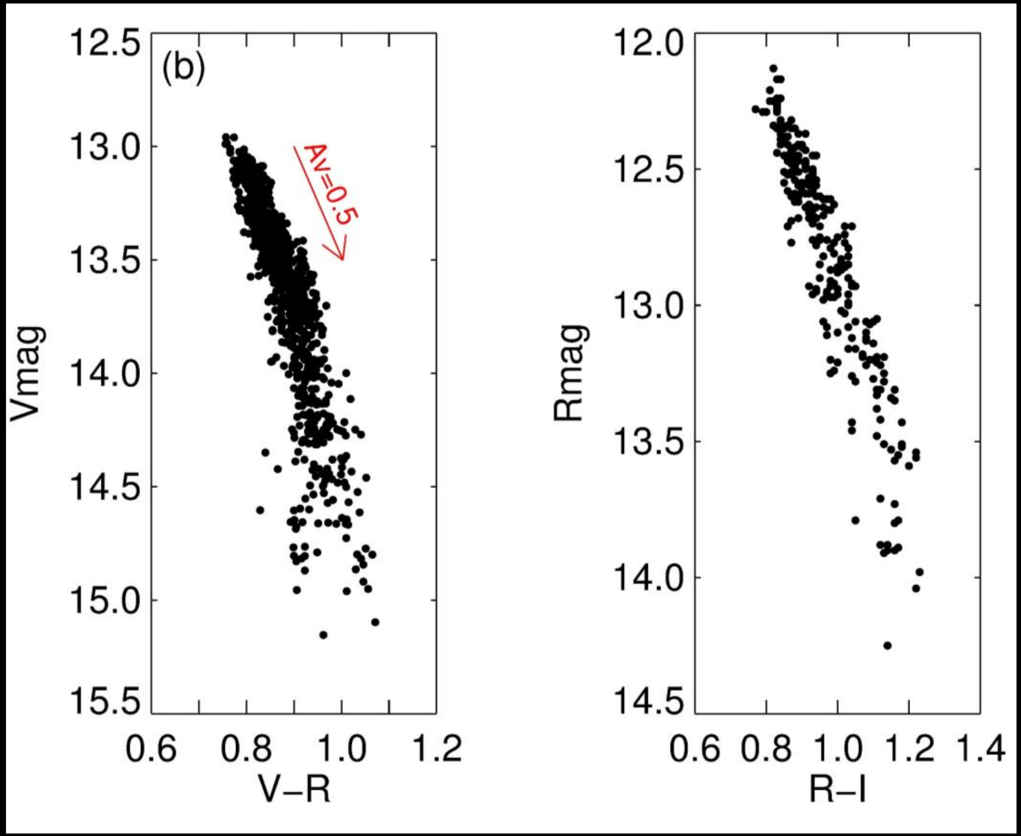
- Dips with sufficient data coverage
- Gaussian → duration (5σ width) and depth
- Short events → depth ∝ duration
  → A_V ~ 1 mag / 30 days

  Long events → A_V ~ 1.5 mag
  → string or spiral arm?



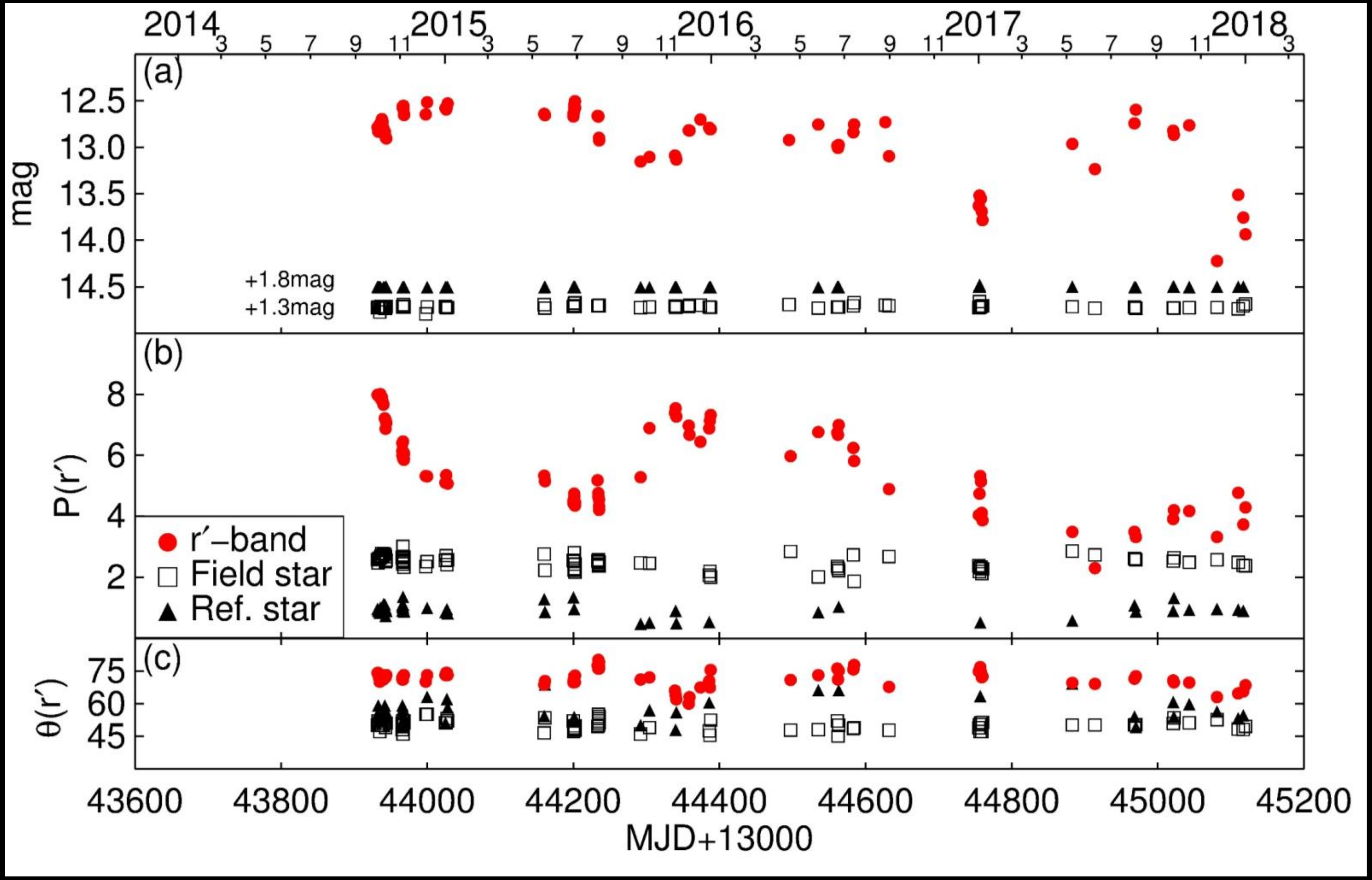
Color variations





- Extinction law of R_v=5 → larger grain size
- Reddening → gray extinction → blueing
- Blueing effect → scattering (Bibo & The 1990; Grinin et al. 1994; Grady et al. 1995, Herbst & Shevchenko 1999)
- Blueing subsides toward long-wave.
  → supporting scattering origin

Polarization



– $P_{r'}$ = 3% - 8% with avg. angle 72°

– Coms.: steadily polarized

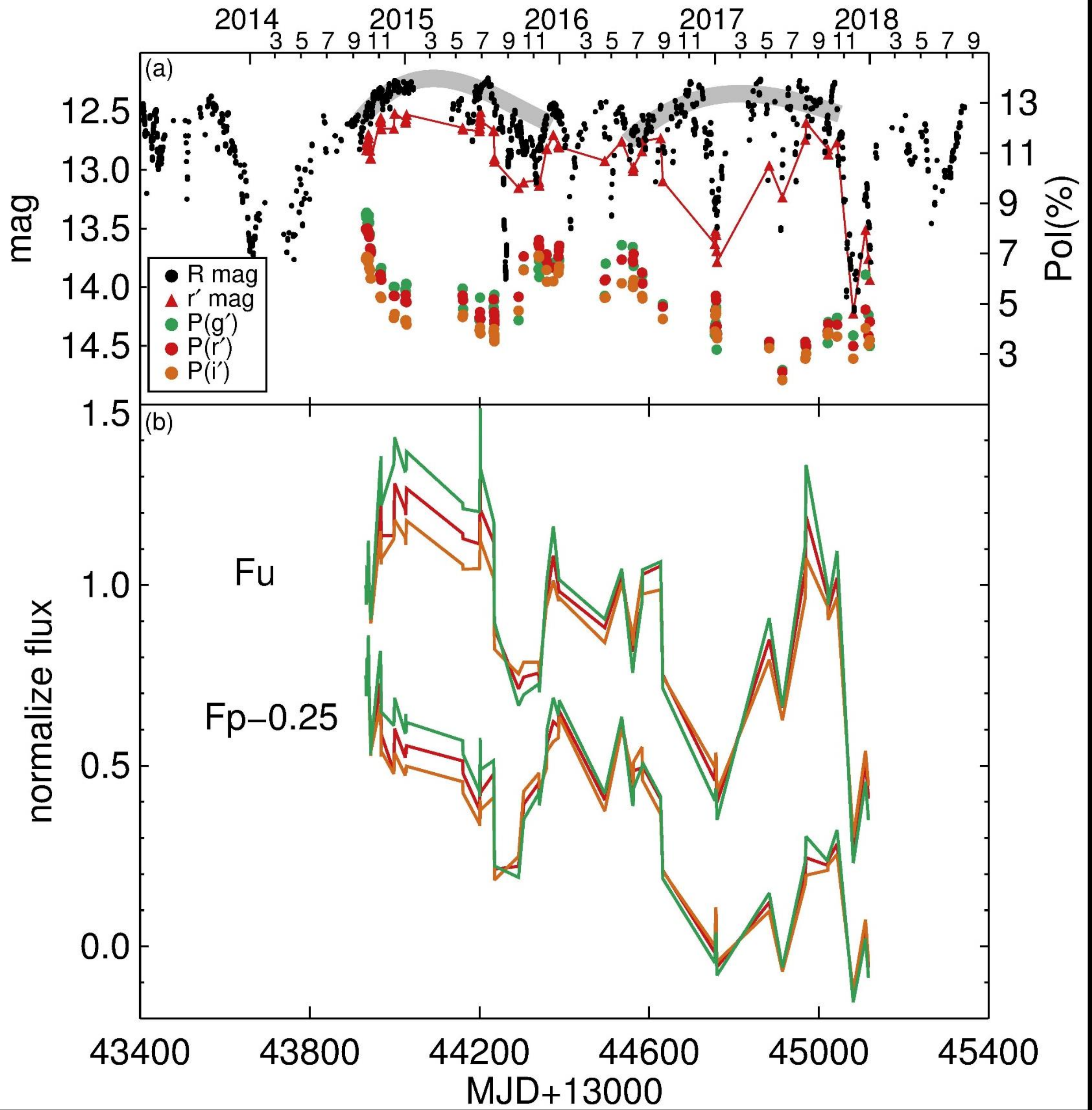
→ variation ≤ 1%

– Adding up 4 polarizer angles

→ total flux

→ simultaneous photometric and polarimetric behavior

Flux from star and envelope



- Slowly varying pattern
  6% — 9% (Oct. 2014)
  → 3% — 5% (Jul. 2015)
  → 5% — 7% (Dec. 2015)
  similarly in 2017 but with variation 2% — 5%
- Brightness has reverse trend

$$P_\lambda(\%) = \frac{F_\lambda^P}{F_\lambda^t} = \frac{F_\lambda^P}{F_\lambda^P + F_\lambda^u} = \frac{1}{1 + F_\lambda^u / F_\lambda^P}$$

- ➢ If F_λ^u constant → $P_\lambda \downarrow$ when $F_\lambda^P \downarrow$
- ➢ If F_λ^u changes → $P_\lambda \uparrow$ when $F_\lambda^u \downarrow$

- Scaled to first point
- In 2014, mag ↑ and P ↓ (**Bright: gF_p > rF_p > iF_p**)
  → $F_\lambda^P \downarrow$ and $F_\lambda^u \uparrow$ → egress process
- At brightness minima → $F_\lambda^u \downarrow$ and $F_\lambda^P \downarrow$
  → shorter wave. has stronger extinction
  (**Faint: gF_p < rF_p < iF_p**)

Summary

- GM Cep exhibits (1) brightness fluctuations ≤ 0.05 mag on time scales of days, due partly to rotational modulation by surface starspots with a period of ~ 3.43 d, and partly to accretion activity; (2) minor flux drops of amplitude 0.2–1.0 mag with duration of days to weeks; and (3) major flux drops up to 2.5 mag, each lasting for months, with a recurrent time, but not exactly periodical, of about 2 years.

- The flux drops arise from occultation of the star and gaseous envelope by orbiting dust clumps of various sizes.

- The star experiences normal dust reddening by large grains, i.e., the star becomes redder when fainter, except at the brightness minimum during which the star turns bluer when fainter.

Summary

- The maximum depth of an occultation event is proportional to the duration, about 1 mag per 30 days, for the events lasting less than ~ 50 days, a result of occultation by clumps of varying sizes. For the events longer than about 100 days, the maximum depth is independent of the duration and remains Av ~ 1.5 mag, a consequence of transiting strings or layers of clumps.

- The $g'r'i'$ polarization levels change between 3% and 8%, and vary inversely with the slow brightness change, while the polarization angle remains constant. Temporal variations of polarization versus brightness, once the total light is decomposed into polarized and unpolarized components, allow diagnosis of the occultation circumstances of the dust clumps relative to the star and envelope.

Thanks for your attention!