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Surface and Atmospheric Structure on the T Tauri Star V2129 Oph

F.M. Walter,[1] E. Falccomio,[2] S. Alencar,[3] C. Argiroffi,[2,4] J. Bouvier,[5] J.-F. Donati,[6] K. Getman,[7] S.G. Gregory,[8] G.A.J. Hussain,[9] M. Ibrahimov,[10] M.M. Jardine,[11] and M.B. Skelly[6]

[1]*Stony Brook University, Stony Brook NY, USA*

[2]*Osservatorio Astronomico di Palermo, Palermo, ITALY*

[3]*ICEx - UFMG, Belo Horizonte, MG, BRAZIL*

[4]*Universita di Palermo, Palermo, ITALY*

[5]*Observatoire de Grenoble, Grenoble, FRANCE*

[6]*CNRS & Universite de Toulouse, Toulouse, FRANCE*

[7]*Pennsylvania State University, University Park PA, USA*

[8]*California Institue of Technology, Pasadena CA, USA*

[9]*ESO, Garching bei München, GERMANY*

[10]*Ulugh Beg Institute, Tashkent, UZBEKISTAN*

[11]*University of St Andrews, St Andrews, SCOTLAND*

Abstract. We provide an overview of a multi-wavelength observing campaign focusing on the accretion and coronal processes in the young star V2129 Oph. V2129 Oph is a classical T Tauri star with a 6.5 day rotation period in the ρ Oph star forming region. On 27-29 June 2009 we obtained two 100 ksec Chandra HETG exposures, aiming at opposite hemispheres of the star. We discuss the X-ray data elsewhere. In order to place the coronal X-ray emission in context, we obtained contemporaneous optical and near-IR photometry and high dispersion optical spectroscopy. The photometry shows the existence of dark photospheric spots. The Hα line profiles show a modulation of the mean Hα velocity and the presence of red-shifted absorption, probably from the accretion stream, at certain phases. Zeeman Doppler images reveal the presence of both a cool spot and an accreting region at similar longitudes.

1. Introduction

Classical T Tauri stars (cTTS) show evidence for magnetic fields, as evidenced by stellar magnetic activity and magnetically-channeled accretion. These magnetic fields can be mapped using Zeeman Doppler Imaging (ZDI) techniques and potential field extrapolations. Surface features, both dark photospheric spots and bright accreting hot spots, can be detected by Doppler imaging techniques. Correlations between the surface brightness maps and the ZDI maps reveal the relation between the magnetic field and surface structures, and permit us to build up a three dimensional view of the stellar atmosphere. Since the hot coronal gas is confined by the closed magnetic field, an observational test of the surface field extrapolations can be provided by observations of the coronal X-ray modulation (Jardine et al. 2008).

V2129 Oph, a relatively massive cTTS, was observed using ZDI techniques in 2005 (Donati 2007), and a strong magnetic field, with both octupolar and dipolar components, was detected. A followup campaign, with better phase coverage, permits a remapping to see if the magnetosphere has changed over 4-5 years. See Gregory et al. (2009) for a more complete description of the aims of this program. The ZDI results of this program are published in Donati et al. (2010); here we present a summary of the surface spectral mapping and a synopsis of the overall results.

2. The Target

V2129 Oph is a classical T Tauri star (ROX 29, SR 9, CD-24 12689, AS 207) located in the ρ Oph star forming region, at a distance of 120 ± 5 pc. The emission lines are fairly weak; the Hα equivalent width varies between about -10 and -20Å. The peak visual magnitude m_V = 11.2; the unspotted m_V is about 11.0. The K5 spectral type is consistent with the 4500K effective temperature. The bolometric luminosity log(L)~0.15 ± 0.1 $L_\odot$. The inferred radius is 2.0 ± 0.3 $R_\odot$. The observed rotation period P_{rot} varies between 6.35 and 6.6 days (Grankin et al. 2008), which suggests that we are seeing differential rotation, with the dark spots changing latitude with time. The projected rotation velocity V sin i = 14.5 ± 0.3 km/s, implying an inclination i~65°. From evolutionary tracks, the mass and age are estimated to be about 1.35 $M_\odot$ and 2-3 Myr, respectively. The mean log(accretion rate) is estimated to be -9.2 ± 0.3 $M_\odot$/yr (Donati 2007; Donati et al. 2010). Surface magnetic fields were measured in 2005, with both octupolar (1.5 kG) and dipolar (0.3 kG) components (Donati 2007; Gregory et al. 2008).

The low mass companion (McCabe et al. 2006), at a distance of 0.6 arcsec, is in the beam for all the observations we report. It contributes less than 10% of the flux at *K*, and, with an estimated mass of 0.1 $M_\odot$, is of no consequence here.

3. The Observing Campaign

We obtained two 100 ksec Chandra HETG observations on 27 and 29 June 2009. Those data are reported elsewhere in this volume (Flaccomio et al.), with a full account in Argiroffi et al. (in preparation). Here we concentrate on the supporting ground-based photometry and spectroscopy.

3.1. Photometry

BVRI/*JHK* photometry was obtained using the SMARTS 1.3m ANDICAM dual-channel photometer at Cerro Tololo from 24 June through 8 July 2009. We supplemented this with *V* and *R* observations from the Palermo Observatory the nights of 23-30 June 2009. These data were obtained with the primary goal of determining the photometric phase (i.e., the location of the dark spots) at the time of the X-ray observations. The ANDICAM data are measured differentially against stars in the field. As V2129 Oph is projected on a dark cloud, comparison stars are few in the ANDICAM field of view (6.2

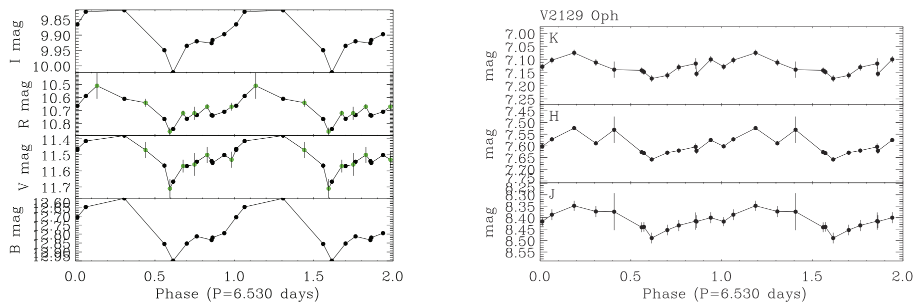

Figure 1. *Left:* Optical photometry from SMARTS/ANDICAM (black) and Palermo (green), folded on the nominal 6.53 day rotation period. *Right:* Near-IR photometry from ANDICAM.

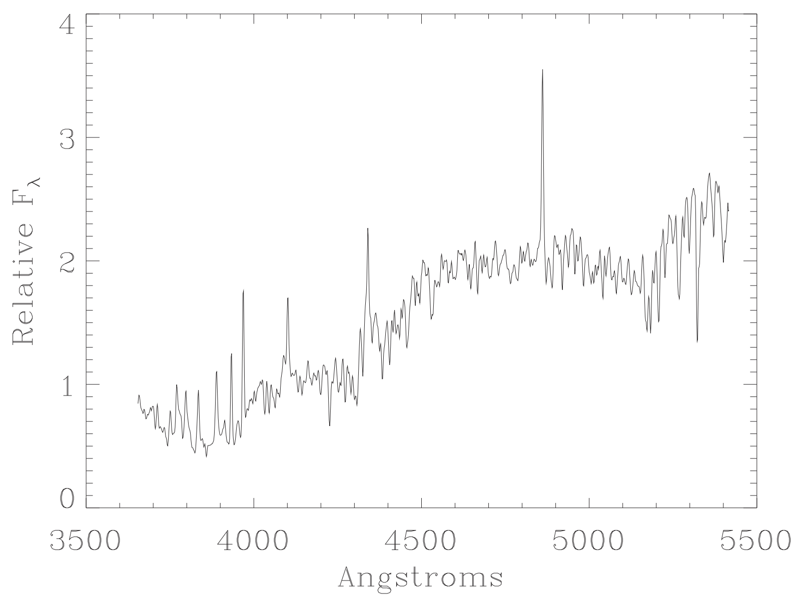

Figure 2. The low dispersion blue spectrum on 27 June 2009. The resolution is 4.3Å. The Balmer lines and the Ca II K&K emission lines are superposed on the K5 photosphere. Veiling is small.

arcmin optical; 2.4 arcmin in the nIR). We used VSSG 14 as the optical comparison, and VSSG 13, a background K giant, as the nIR comparison. Conversions to apparent magnitude are done by calibrating the optical comparison on photometric nights, and by using the 2MASS magnitude of the nIR comparison.

The data folded on the 6.53 day period are shown in Figure 1. The amplitude of the modulation is a smooth function of wavelength, decreasing from 0.14 mag at *B* to 0.03 mag at *K*. A simple model of dark spot gives T_{spot}=3880K with a filling factor of 11%. Minimum brightness occurred at JD 2455012.3±0.2.

3.2. Spectroscopy

We obtained low dispersion spectra using the SMARTS 1.5m RC spectrograph every few weeks beginning in March 2009, and with a higher cadence from 19 June through 8 July 2009. We took spectra with 3 setups (one setup per night); conditions were often adverse during the Chilean winter. The blue spectrum taken close to the time of the first X-ray observation is shown in Figure 2.

We also obtained high resolution spectra from 3 sources: the SMARTS 1.5m echelle, the CFHT 3.5m ESPaDOnS (for Zeeman Doppler Imaging), and the ESO 3.6m HARPS. The ESPaDOnS ZDI data are reported by Donati et al. (2010). The HARPS and SMARTS data are being used to examine the line profile variations, and perform Doppler image mapping. The line profiles are highly variable (see Figure 3), but are reproducible as a function of phase. The Hα profile exhibits significant changes in both centroid wavelength and line width, which are better seen in the stacked HARPS spectra (Figure 4).

There were no large flares during the time of the X-ray observations (the very broad Hα profile on day 5023 [Figure 3] is probably a flare, but this occurred about 12 days after the end of the X-ray observations). On the whole the spectra were unremarkable during the time of the X-ray observations.

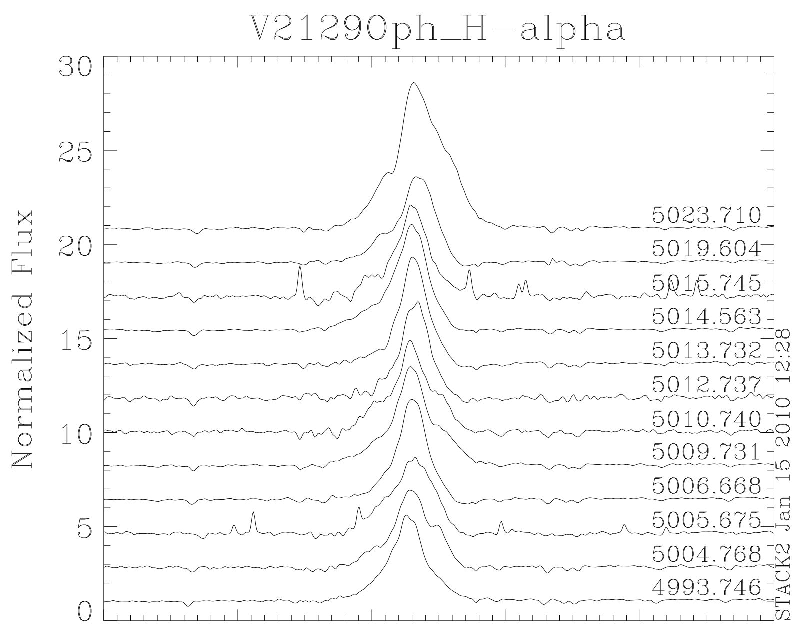

Figure 3. The SMARTS echelle spectra. A 150 Å long swath centered near Hα is plotted. The data span the interval 11 June through 11 July 2009 (the numbers on the right are JD-2450000). Resolution is about 30,000. Spectra are normalized to the continuum, and offset upwards. The spectra are the median of three 20 minute integration, except on nights 5005 and 5015, when weather conditions limited us to a single 20 minute exposure. Apparent narrow emission features are unsubtracted cosmic rays on the nights when we were limited to simgle exposures.

The mean velocity of the photospheric absorption lines, -7.2 km/s, agrees with the velocities in the literature. The mean velocity of the Hα emission centroid lies about 6 km/s blueward of that, but the centroid velocity is modulated by ±20 km/s on the stellar rotation period. This reflects the fact that the accretion is concentrated in a small part of the star.

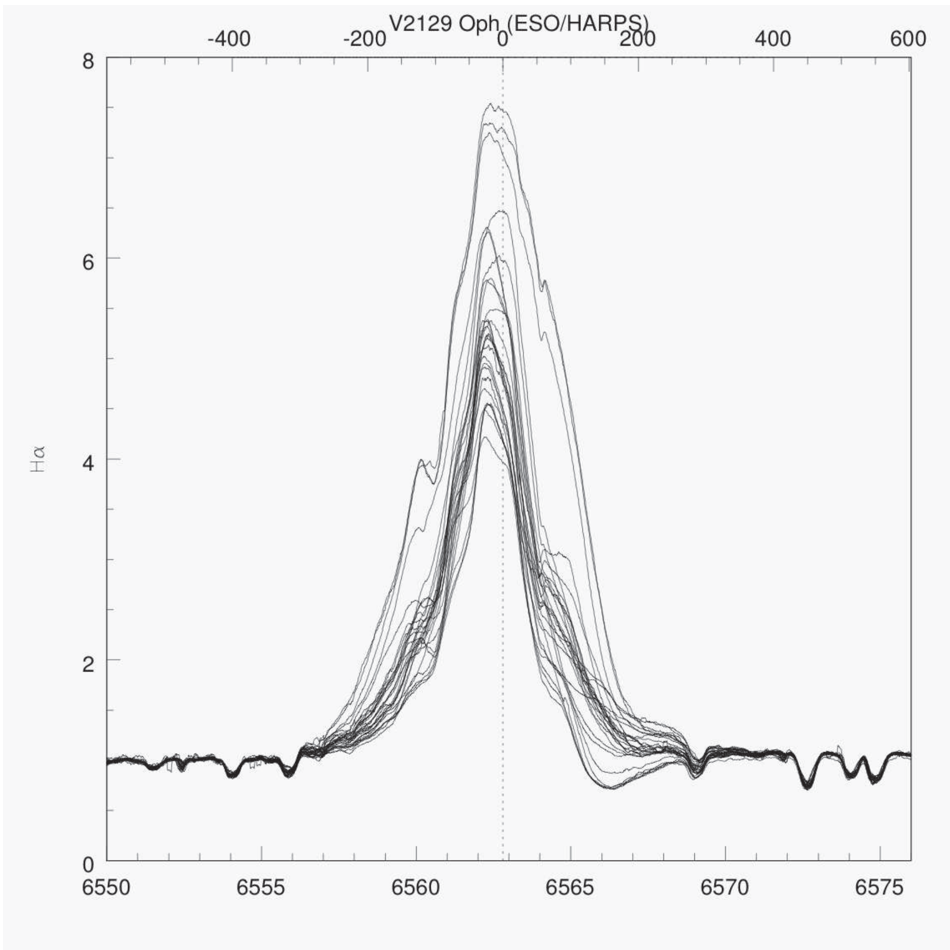

Figure 4. Hα line profiles from the HARPS spectra. The line profile changes with time. The notch in the blue wing, at a velocity of about 150 km/s, is most prominent at phases 0.2 - 0.5. The redshifted absorption occurs at phases 0.6-0.9. The dotted line marks the photospheric radial velocity.

The Hα line profile shows notches on both the red and blue wings, and a clear inverse-P Cygni profile at certain phases. There are two distinct infall velocities seen as the line of sight passes through the accretion stream. Notches on the blue side of the line are due to absorption in the stellar wind. These too are modulated with rotational phase.

A combination of the Doppler imaging and ZDI maps shows that the strongest radial magnetic field, the most prominent dark region and the accretion-heated hot spot are nearly co-spatial, and about 20° from the rotation axis (Donati et al. 2010).

4. Summary

Over a few rotation periods, rotational modulation of the surface features dominates over stochastic variability. The Doppler maps (Donati et al. 2010) seem to represent true surface structures that survive for many stellar rotations.

The large scale magnetic field is axisymmetric and poloidal. The total field strength increased by a factor of 2 over the 4 years between maps. The size of the dark spot has similarly increased. The dominant octupolar field of 2005 was replaced in 2009 by a dominant dipolar field, but both components remain. The dipole strengthened more than the optupole.

The 4 kG high latitude radial magnetic field remains in about the same location on the star as in 2005.

The accretion shock, the base of the accretion stream, is seen as brightness enhancements in He I and Ca II Doppler maps. It is near the region of strongest radial field, but trails the dark spot by 40° in longitude.

The rotation period, from the Doppler modeling, is 6.53 days.. This period is in the middle of the observed distribution of P_{rot}, as expected, and represents the mean mid-latitude rotation period. Our photometry is consistent with this period. Donati et al. (2010) measured the differential rotation, the shear dΩ, to be 0.036 ± 0.015 rad d^{-1}, or about half the solar value. The range of observed P_{rot} is consistent with spot migration and the observed the shear dΩ.

We are working on refining the Doppler maps in various diagnostic lines, in order to probe the three dimensional structure of the atmosphere and the accetion stream. At the same time, comparison of the X-ray emission measure distribution with that predicted from the potential field extrapolations will probe the structure of the stellar corona.

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