T.C.
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BİLİMSEL ARAŞTIRMA PROJELERİ
KOORDİNASYON BİRİMİ

Astronomi ve Uzay Bilimleri Bölümü'nde Optik Teleskop Kurulumu ve Seçilmis Çift Yıldızların Fotometrik Gözlemleri ve Analizi

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KAYSERİ

TEŞEKKÜR

Yürütücülüğümde gerçekleştirilen FBA-09-770 numaralı bu proje, Erciyes Üniversitesi Bilimsel Araştırma Projeleri Birimi (ERÜ BAP) tarafından desteklenmiştir. Proje sürecinde gerekli malzemelerin alımı konusunda yol göstericilikleri ve işlerin sorunsuz yürütülmesindeki çabalarından dolayı tüm ERÜ BAP çalışanlarına teşekkürü bir borç biliriz. Bu proje, Erciyes Üniversitesi Astronomi ve Uzay Bilimleri Gözlemevi Araştırma ve Uygulama Merkezinin (UZAYBİMER) himayesinde yürüyen bir projedir. Proje kapsamında alınan malzemelerin korunmasında ve bundan sonraki süreçte teleskop ve ekipmanlarının monte edilmesinde UZAYBİMER'in katkısı şüphesiz belirleyici olmuştur/olacaktır. Tüm bu çabalarından dolayı UZAYBİMER'e kurum olarak ve çalışanlarına ayrıca teşekkür ederiz.

Proje Ekibi Adına

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İÇİNDEKİLER

	Sayfa No
TEŞEKKÜR	i
ÖZET	1
ABSTRACT	2
1. AMAÇ VE GEREKÇE	3
2. LİTERATÜR BİLGİSİ VE LİSTESİ	5
3. GEREÇ VE YÖNTEM	9
4. TARTIŞMA VE SONUÇ	10
5. EKLER	11

ÖZET

FBA-09-770 numaralı proje ile esas amaçlanan, Erciyes Üniversitesi Astronomi ve Uzay Bilimleri Gözlemevi Araştırma ve Uygulama Merkezi'ne (UZAYBİMER) bir optik teleskop kazandırmaktır. Böyle bir teleskop, Üniversite kampüsü içinde lisans ve lisansüstü öğrenciler için bir laboratuar ortamı sağlayacak ve onlara derslerde öğrendiklerinin uygulamasını yapma imkanı verecektir. Bu teleskop ile bazı yüksek lisans öğrencilerinin ihtiyaçları olan tez verilerinin elde edilmesi de amaçlanmıştır. Ayrıca, önemli astronomik olaylarda, popüler anlamda halkı bilgilendirmek amacıyla da bu tür teleskoplara, Üniversite ve UZAYBİMER olarak, ihtiyacımız vardır. Bu amaçla proje kapsamında 40 cm'lik bir optik teleskop alınmıştır. Bundan sonraki aşamada teleskobun işler hale getirilebilmesi için, UZAYBİMER tarafından bir kubbe sistemli bina yapılarak teleskobun uygun şekilde bu binaya monte edilmesi gerekmektedir.

Anahtar Kelimeler: UZAYBİMER – Gözlemevi, Teleskop.

ABSTRACT

The main aim of this project called FBA-09-770 is updating an optical telescope in behalf of Erciyes University Astronomy and Space Sciences Research Center(UZAYBİMER). This telescope is to provide a laboratory for both undergraduate and graduate level courses and an opportunity for application of student's theoretical knowledge. We also aim to obtain scientific data for some grad level students and for their thesis. In addition, we would like to use this telescope for outreach and knowledge sharing events in UZAYBİMER of ErU. Considering these aims we bought a 40 cm optical telescope by this project in behalf of UZAYBİMER. At this point, it is necessary for UZAYBİMER to provide an operation building and a dome system to operate this telescope properly.

Keywords: UZAYBİMER – Observatory, Telescope.

1. AMAÇ VE GEREKÇE

Astronomi, gözlemsel yanı ağır basan bir temel bilim dalıdır. Üniversitelerde verilen, lisans düzeyindeki temel astronomi öğretimi, gözlemsel olarak da pekiştirilmediği sürece, öğrenci bazında anlaşılırlığı zor olmakta ve eğitim ayağı eksik kalmaktadır.

Gözlemsel astronomi için teleskopa ihtiyaç vardır. Bölümümüzün bilimsel misyonu Radyo astronomi alanında gerekli çalışmaları başlatmak ve Türkiye çapında kurulması düşünülen bir Ulusal Radyo Astronomi Gözlemevine deneyimli elemanlar yetiştirmektir. Bu amaçla bölümümüzde bir radyo çanak kurulumuna yönelik bir DPT projesi yürütülmektedir. Ancak bu misyon, lisans üstü eğitim için düşünülmüştür ve bir astronomi bölümünün elektromanyetik tayfın tek bir aralığında gözlemsel imkanlara sahip olması düşünülemez. Özellikle lisans eğitiminde verilen derslerin gözlemsel ayağı daha çok optik astronomi ile ilgilidir.

Ülkemizdeki üniversitelerin dört tanesinde Astronomi ve Uzay bilimleri eğitimi lisans düzeyinde (Ankara, İstanbul, Ege ve Erciyes Üniversitesi), ve bir çok üniversitede de lisans üstü düzeyde, fizik bölümlerinin altında Astrofizik eğitimi verilmektedir (ODTÜ, Bogaziçi, İnönü, Akdeniz, Anadolu, Çukurova, Atatürk, Çanakkale 18 Mart ve Ahi Evran). Lisans düzeyinde astronomi ve uzay bilimleri bölümü olan her üniversitenin, lisans ve lisans üstü öğrencilerinin derslerinde ve tezlerinde ve akademik kadronun da bilimsel araştırmalarında kullanabilecekleri bir gözlemevleri ve teleskopları vardır. Bunun dışında yukarıda sayılan diğer üniversitelerin de bir çoğunda fizik öğrencilerinin kullanabildiği bir optik teleskop mevcuttur (ODTÜ, Çukurova, İnönü Üniversitesinde, 1 adet 40 cm'lik teleskop; Anadolu, Ahi Evran Üniversitesinde bir adet 30 cm'lik teleskop; Çanakkale 18 Mart Üniversitesinde bir adet 40cm'lik, 2 adet 30 cm'lik ve yakında hizmete girecek 1.2 metrelik bir büyük teleskop. Not: Bu teleskop hizmete girdi.).

Anlaşıldığı üzere, yakın zamanlarda kurulmuş (1999) ve ilk mezunlarını 2007 yılında vermiş olan Erciyes Üniversitesi Fen Edebiyat Fakültesi Astronomi ve Uzay Bilimleri Bölümünün gözlemsel çalışmaları eksik kalmıştır. Bölümümüzde verilen lisans eğitimi için öğrencilerin bir laboratuar olarak kullanabilecekleri, içinde bir optik teleskop olan gözlemevine ihtiyaç vardır. Söz konusu teleskop aynı zamanda, bölümümüzde yüksek lisans öğrencilerinin de tezlerinde ihtiyaç duyacakları verinin elde edilmesinde kullanılabilecektir. Ayrıca bölüm akademik kadrosunun bilimsel araştırmalarında da, tüm Türk astronomların yoğun kullanımı nedeniyle yeterli proje zamanı alınamayan TÜBİTAK ulusal gözlemevine (Antalya) bağımlılığı azaltacaktır.

Bölümümüz, sadece üniversite öğrencilerine yönelik degil, sürekli egitim kapsamında halka yönelik eğitim çalışmalarına da önem vermektedir. Bu amaçla, önemli gök olaylarına denk gelen günlerde halk günleri düzenlenmekte ve orta öğretim öğrencilerine yönelik bilgilendirme seminerleri verilmektedir. Bölümümüze alınacak bu tür bir teleskop bu hizmetlerin daha iyi verilmesini sağlayacaktır.

Bu proje kapsamında alınması istenilen teleskop, bölüm eğretim elemanları ve lisansüstü öğrencilerin bilimsel çalışmalarına önemli katkılarda bulunacaktır. Mevcut durumda, araştırmalar için TUG olanakları kullanılmaktadır. Ancak TUG tüm Türk astronomlara hizmet verdiği için gözlem zamanı almak son derece zor olmaktadır. Bölümümüz bünyesinde sahip olacağımız bir teleskop hem bilimsel araştırmalar için hem de öğrencilerin yetişmesi için büyük katkı sağlayacaktır. Diğer gözlemevlerinde benzer teleskoplarla yapılan bilimsel çalışmalar ve proje kapsamında gözlemi düşünülen cisimler, "8. Literatür Bilgisi ve Listesi" bölümünde verilmiştir.

Bu proje ile, Erciyes Üniversitesi Fen Edebiyat Fakültesi Astronomi ve Uzay Bilimleri Bölümüne 40cm'lik bir teleskopun ve ilgili teçhizatlarının alınması ve çalışır duruma getirilerek, projede belirtilen bilimsel çalışmaların yapılması amaçlanmaktadır.

Verilen proje, özü itibari ile Astronomi ve Uzay Bilimleri Bölümüne bir optik teleskop kurulmasını amaçlamaktadır. Ancak, teleskop ve gerekli ekipmanların toplam fiyatı, Bilimsel Araştırma Projelerinin maksimum miktarı olan 30 000 YTL'yi geçmektedir. Bu nedenle, esas proje iki parçaya ayrılarak, Ögr. Gör. Dr. Mehmet Tanrıver'in verecegi "OB Bileşenli Erken Tür Çift Yıldızların Işık Egrisi Analizi ve Fiziksel Parametrelerinin Belirlenmesi" konulu proje ile birleştirilmesi düşünülmüştür. Bütçe kısmında belirtilen parasal degerler, EK1 dosyasında ve online giriş yapılırken gerçek miktarların yarısı kadar girilmiştir. Proje kabul edilir ve iki proje birleştirilirse harcama kalemleri yaklaşık iki katına çıkacaktır. Proje incelemesi sırasında bu durumun dikkate alınması önemlidir.

2. LİTERATÜR BİLGİSİ VE LİSTESİ

Burada, diğer üniversite gözlemevlerinde benzer teleskoplarla yapılan gözlemlerden elde edilen sonuçların ne tür yayınlara dönüştürüldüğünü vermek uygun olur. Öncelikle, yapılan yayınların SCI'da taranan A sınıfından baslayarak her türlü bilimsel dergide olabilecegini belirtmek gerekir. Söz konusu yayınlar, o üniversitelerde yapılan lisansüstü tezlerin bir parçası veya bireysel bilimsel araştırmaların bir sonucu olarak ortaya çıkmaktadır.

Burada Ankara, Ege ve Çanakkale 18 Mart Üniversitesi Gözlemevlerinde benzer teleskoplarla yapılan bilimsel çalışmalardan son beş yılda elde edilen yayınların seçilmiş bir listesi ve sonra proje kapsamında gözlemi düşünülen yıldızların bir literatür bilgisi verilmiştir.

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Projede gözlemsel olarak incelemesi yapılacak cisimler üç gruba ayrılmıştır. Birinci gruptakiler, daha önceden çesitli şekillerde gözlemsel olarak incelenmiş ve proje elemanlarının da içinde bulunduğu yayınlar yapılmış olan yıldızlardır. Bu yıldızlar, ışık değişimi ve yörünge dinamikleri gereği gözlemsel olarak sürekli takibi gereken sistemlerdir. Bunlar, HD 10308, HD 483, CQ Cep, IU Aur, ve TT Aur çift sistemleridir.

Bu sistemlerden HD 10308 ve HD 483, 2007 ve 2008 yılı içinde TUG’da tayfsal olarak gözlenmiş ve HD 10308’de tayfsal analizler sonucunda sistemde bir tutulma görülmesi gerektiği sonucuna varılmıştır. Yaklasık 4.4 gün dönemli bu sistemin literatürde tam bir ışık eğrisi gözlemi yoktur ve tutulma göstermediği söylenmektedir, sistemin yeni fotometrik gözlemlere ihtiyacı vardır. Tayfsal gözlemlere ilişkin analizler, 15-19 Eylül 2008 tarihlerinde Çek Cumhuriyetinde yapılan bir bilimsel yaz okulunda bildiri olarak verilmistir (Hasan Ak, Nurten Filiz Ak, 2008).

HD 483 sistemi, dönemi yaklasık 24 gün kadar olan, Güneş benzeri iki bileşenden oluşan bir çift sistemdir. Güneş’te görülen manyetik aktivitenin, bu sistemin bileşenlerinde olup olmadığını araştırmak ve çiftlik etkisinin bunu ne ölçüde etkilediğini görmek için bu tür sistemlerin çalışılması gerekmektedir. Sistemin analiz için yeterli olmayan, TUG’da alınmış birkaç tayfsal gözlemi vardır, ancak fotometrik olarak gözlemi son derece yetersizdir.

CQ Cep, WR bileşenli bir büyük kütleli OB çift sistemidir. Sistem etrafında WR ve O bileşeninden kaynaklanan yoğun rüzgar nedeniyle sistemi saran bir zarf mevcuttur. Bu zarf ve yoğun rüzgar, sistemin radyal hız eğrisinin sağlıklı belirlenememesine ve fotometrik ışık eğrisinin sürekli değişiklik göstermesine neden olmaktadır. Sistemin literatürde iyi elde edilmiş bir çok ışık eğrisi vardır, ancak değişim nedeniyle sürekli takibi gerekmektedir. Sistem ile ilgili belli başlı yayınlar, Underhill, A.B. (1983), Marchenko, S. V. et al. (1995) ve Demircan, O., Ak, H., Özdemir, S., Tanrıver, M. And Albayrak, B. (1997) çalısmaları verilebilir.

IU Aur sistemi de büyük kütleli bir OB çift sistemidir. Sistemi ilginç kılan, çiftli sisteme çekimsel olarak bağlı olan bir üçüncü bileşenin olması (muhtemelen bu üçüncü bileşen de kendi içinde çift) ve çift sistemin yörünge düzlemi ile bu üçüncü bileşenin yörünge düzlemlerinin tam çakışık olmaması nedeniyle, çift sistemin yörünge düzleminin presesyon hareketi yapmasıdır. Bu hareketin bir sonucu olarak, çift sistemin yörünge eğim açısı sürekli degişmekte ve bu değişim ışık eğrisine minimum derinliklerinin degişimi olarak yansımaktadır. Literatürde bu türde değişim gösteren çok az sayıda sistem vardır. Bu değişimin karakteri tam olarak belirgin degildir ve sürekli gözlemlere ihtiyaç vardır. Sistem ile ilgili önemli yayınlar, Mayer, P. (1983), Mayer, P and Drechsel, H. (1987) ve Özdemir, S., Mayer, P., Drechsel, H., Demircan, O. And Ak, H. (2003) olarak verilebilir.

TT Aur sistemi de bir çift ve üçüncü bileşen içeren bir üçlü sistemdir. Yörünge dinamiğinin iyi anlaşılabilmesi için bu tür sistemlerin düzenli bir şekilde minimum zamanlarının gözlenmesi gerekmektedir. Sistemin genel çalısmaları, Popper, D. M. and Hill, G. (1991), Simon, V. (1999) ve Özdemir, S., AK, H. et al. (2001) tarafından yapılan çalısmalardır.

İkinci grup olarak belirlenen yıldızlar, çeşitli nedenlerle (bileşenler arası kütle aktarımı veya sistemden kütle kaybı, manyetik çevrim, üçüncü cisim etkisi, eksen dönmesi gibi) yörünge dönemi değişimi gösteren ve düzenli olarak minimum zamanı gözlemine gerek duyulan cisimlerdir. Bu tür sistemlerin düzenli minimum zamanı gözlemleri yapılarak, elde edilen sonuçlar yılda iki kez IBVS'de yayınlanacaktır. Proje elemanlarının bu türde yayınları mevcuttur (IBVS: 5174, 5361, 5462).

Üçüncü grup yıldızlar da, Hipparcos uydusu (Perryman M. A. C. et al. 1997) ve ASAS (All Sky Automated Survey, Pojmanski, G. 2001) gibi genel tarama gözlemlerinde değisen olduğu keşfedilen yıldızlar arasında, parlaklık ve konum olarak gözleme uygun cisimlerden oluşmaktadır. Bunların ayrıntılı fotometrik gözlemlerinin elde edilmesi ve fotometrik yörünge çözümünün yapılması, literatüre yeni bilgi olarak katkı sağlayacaktır.

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3. GEREÇ VE YÖNTEM

Proje ile alımı düşünülen teleskobun gözlem yapabilir duruma gelmesi için bir takım ek donanıma ihtiyaç vardır. Bunlar, günümüz modern teleskoplarında, teleskop kadar önemli olan ekipmanlardır.

Teleskop odağında toplanan ısığın algılanması ve fotometrik gözlemler için bir CCD dedektör, farklı dalgaboylarında gözlem yapma imkanı verecek bir filtre seti ve bu filtreleri otomatik sürecek bir filtre tekeri ve tüm donanımı ve teleskobu kontrol edecek yüksek hızlı bir bilgisayara ihtiyaç vardır.

Fotometrik gözlem sırasında kullanılan CCD dedektörün kontrolü ve verinin bilgisayar ortamına kaydedilmesi lisanslı bir program aracılığıyla yapılmaktadır. Teleskop ve diğer ekipmanlar ile beraber böyle bir programın da alınması gerekmektedir. MaxIm DL adlı bu program aynı zamanda astronomik gözlem verilerinin indirgenmesinde de kullanılacaktır.

İndirgenmiş gözlem verileri, uygun analiz programları (çift sistemlerin ışık eğrileri çözümü için Wilson-Devinney (Wilson and Devinney 1971), FOTEL (Hadrava 1992) , Binary Maker (Bradstreet and Steelman 2004) gibi programlar) ile analiz edilerek yayına hazır hale getirilecek ve uygun dergilerde yayınlanacaktır. Tutulma gösteren çift sistemlerin minimum zamanları sistematik bir şekilde gözlenecek ve yılda iki kez olmak üzere "Information Bulletin on Variable Stars (IBVS)" adlı yayın organında yayınlanacaktır.

4. TARTIŞMA VE SONUÇ

Yukarıda Özet ve projenin ana bölümlerinde vurgulandığı üzere, bu projenin esas amacı, Erciyes Üniversitesi UZAYBİMER Araştırma ve Uygulama Merkezine bir optik teleskop kazandırmaktır. Böyle bir teleskop, Astronomi ve Uzay Bilimleri Bölümü öğrencilerinin derslerde öğrendikleri teorik bilgiler için bir laboratuar imkanı sağlayacak, lisansüstü öğrenciler için onların tez çalışmalarında kullanabilecekleri verinin elde edilmesinde önemli bir araç olacaktır.

Üniversitelerin bir amacı da sürekli eğitim anlayışı gereği, bilginin halka indirilmesidir. Bu teleskobun kurulumu ile beraber, geniş halk kitlelerinin çok meraklı olduğu önemli astronomik olaylarda, Kayseri'de Üniversite olarak halkı bilgilendirme etkinlikleri düzenleyebileceğiz.

Bu proje verilirken, alınan teleskop ile yapabileceğimiz bazı bilimsel çalışmaların bir örneğini de vermiştik. Ancak bu çalışmaların gerçekleştirilebilmesi için teleskobun, kubbe sistemli bir bina içine monte edilip gerekli kurulumundan sonra, çalışır vaziyete getirilmesi gerekmekte idi. Ne yazık ki, teleskobun alımından bu güne kadar, proje elemanlarının kontrolü dışında olan bu süreç, başarılı bir şekilde yürütülüp teleskop ilgili binaya monte edilip gözleme hazır hale getirilememiştir.

Gelinen noktada, UZAYBİMER yönetiminde yapılan değişiklik sonrası varılan karara göre, teleskop binası yapımı için yeni bir proje verilmesi sonucu ortaya çıkmıştır. Bu durumda da proje yürütücüsü üzerinde zimmetli görünen teleskobun, UZAYBİMER'e devri sözkonusu olacaktır.

Bu nedenle proje ekibi olarak, yürütücüsü olduğum bu projenin kapatılıp, teleskobun devrinin yapılmasını istiyoruz.

Ekler bölümünde doğrudan bu teleskop ile elde edilen verilerle değil ama teleskobun çalışması durumunda bu teleskop ile yapılabilecek çalışmalara bir örnek olması açısından, proje elemalarının içinde bulunduğu yayınlar konulmuştur.

5. EKLER (Proje elemanlarının ilişkili makaleleri)

High Resolution Coude Echelle Spectroscopy of IX Per

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Abstract. High resolution (R=45000) Coude - Echelle spectra of IX Per has been obtained at TÜBİTAK National Observatory (TUG) of Turkey. IX Per has been known to be a single lined (SB1) spectroscopic binary having chromospheric activity. However, analyzed spectra of IX Per by *KOREL* disentangling method indicated that the system is a double lined (SB2) spectroscopic binary. Weaker lines from the secondary are discovered on the decomposed spectra. A preliminary orbit indicates that the mass ratio of the system is 0.64. The light contribution of the secondary is up to 10% in investigated spectral region. Circular orbit is sufficient to explain radial velocity variations.

Keywords: binaries: general , stars: individual: IX Per , techniques: radial velocities , techniques: spectroscopic
PACS: 95.10.Eg

INTRODUCTION

IX Per (HD 22124, F2IV) is a spectroscopic binary with an orbital period of ~ 1.32 days which were classified as an ellipsoidal variable by Morris [9]. Its radial velocity variations were discovered by Young [15]. One year later, its radial velocity curve was published by Northcot [10], who analyzed the system as a single lined spectroscopic binary. F2 spectral class, which was suggested by Northcot [10], has been confirmed and the luminosity class IV or V was determined on a low dispersion (76 Å/mm) spectrograms, well exposed at UV, which failed to show any evidence of a hot companion by Thomsen et al. [14]. These authors also studied the light curves of the system. Double humped light curve were thought to be produced by eclipses, however, times of light minima were found not matching the conjunction of the system according to the radial velocity curve. Thus, variations were explained as the result of primary stars, which was assumed to be an ellipsoidal shape.

Morris [9], who studied ellipsoidal variables, included the system in his study list. Singh et al. [13] were suggested the system as an RS CVn binary because its UV spectrum displays some strong high-temperature emissions lines also its radio properties [2]. Hipparcos measured its parallax as 14.75 mas and gave light curve of the system, but it is very scattered, therefore clean light curve of the system is needed. The best light curve of the system is the one which was studied by Thomsen et al. [14], but it was wrongly interpreted. The time of the study coincides to the period, when astronomers

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avoided starspots. Starspots was popular before Russel [12] and used to explain all kinds of starlight variations. Starpots only become popular in the second half of the 20^{th} century (see reviews by Kopal [7], Hall [6]). Appearance of the shape of the light curve by Thomsen et al. [14] indicates that the possible source of variations is starspots.

In this study, we are interested in studying the system spectroscopically. We studied the high resolution coude echelle spectra of IX Per. We have discovered that the system is a double lined spectroscopic binary.

OBSERVATION AND DATA REDUCTION

All observations were taken at the TÜBİTAK National Observatory (TUG, 36° 49' N, 30° 20' E) of Turkey with the 150 cm reflector by using high-resolution coude echelle spectrograph (CES). The telescope has 78 meter focal length in coude focus. Observations were made 5 consecutive nights between 7 and 11 October 2007. A total of 24 spectra have been obtained for IX Per. CES is designed to provide wavelength coverage from 3900 to 8500 Åin 68 echelle orders. There are some small gaps, about 5 - 10 Å, between 5000 to 8000 Åorders and some overlapping from 3900 to 5000 Åorders. CES has a resolution about $R = 45000$ with 1Kx1K liquid nitrogen cooled CCD detector.

Exposure time of each stellar spectrum was determined to get a desired signal to noise ratio (S/N) which was ~130, around 5500 Å. All spectra reduced with *DECH* code (Galazutdinov [3]), and wavelength calibrations were made by using $Th-Ar$ arc lamp. Instrumental and heliocentric shifts applied to all spectra. In the end of reduction all spectra was normalized to 1 for analysis.

ORBITAL SOLUTION AND ANALYSES

The spectra of IX Per were analyzed using *KOREL* spectral disentangling by Fourier transform method (Hadrava [4], Hadrava [5]), which yields directly the orbital parameters and decomposed spectra of component stars up to 5. It means that the *KOREL* code also can make orbital solutions. The *KOREL* code was applied to IX Per spectra with the initial orbital parameters (P, T_0, K_1) taken from Northcot [10]. Orbital eccentricity was assumed 0.0 in the beginning and mass ratio, q, was determined with *KOREL* from the disentangled components spectra. Thus, *KOREL* solution strongly indicates existence of secondary companion which contributes the observed spectra up to 10%.

All orbital parameters, except e and w, were iterated and converged to a unique solution. Figure 1 shows observational spectrum and superimposed *KOREL* fitting of each spectrum, and disentangled components spectra.

We have used the spectral lines of echelle order 33, which cover 5439 to 5484 Å, during first trials of *KOREL* fitting process since lines of this order are sufficiently clear and there exist well defined continuum. During the convergence process, circular solution was sought. *KOREL* does not derive systemic velocity, but it measures the shift of components relative to disentangled spectra in which the systemic velocity is retained. We derived the systemic velocity from the cross correlation technique in *DECH* code. After the first trials, founded solution for circular orbit was applied to all orders. Circular

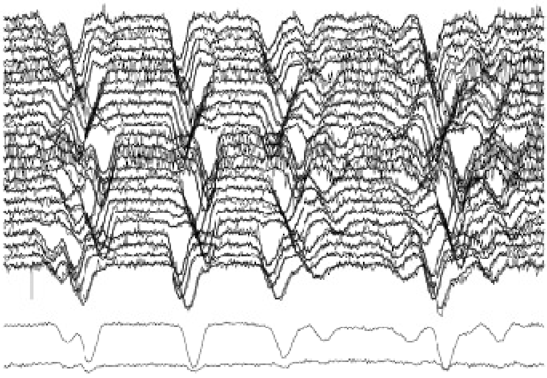

FIGURE 1. Observational spectra and superimposed KOREL fit are seen on top of figure and disentangling spectrum of components at bottom.

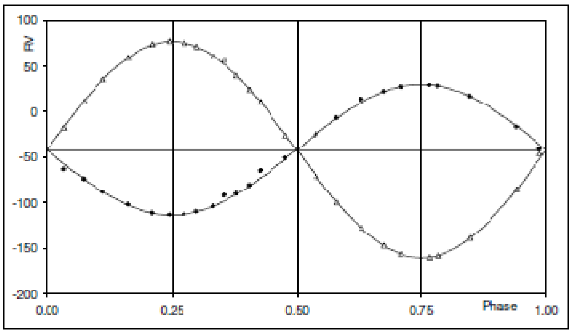

FIGURE 2. The RV curves of IX Per fitted to the KOREL measurements. Filled circles show RV of primary component.

and elliptic orbital solutions from 33rd order are given in Table 1.

The radial velocities (RV) of components were measured from the photospheric lines of Fe I $\lambda\lambda$ 5445.924, 5455.618, 5463.285 and 5476.572 in Åfrom 33^{rd} order of CES. The RV curve of IX Per is shown in Figure 2 for the circular solution.

Modeling with Synthetic Spectra

Synthetic spectra taken from Coelho et al. [1] were applied to the decomposed spectra of primary component. We have found the best fit between synthetic and decomposed spectrum for primary by taking temperature of 6500 K, log g of 3.5 and vsin i of 45 km s^{-1} in solar metallicity. Decomposed and synthetic spectrum fit of primary between 5440-5480 Åand also H_α and H_β region are given in Figure 3.

TABLE 1. Orbital Parameters of IX Per obtained by KOREL and compared to Northcot 1940 solution

Parameteres	Circular Orbit	Elliptic Orbit	Northcot(1940)
T_0	54382.4178	54382.4178	29146.81
P (days)	1.326488	1.326488	1.32639
e	0.0	0.0104	0.024
K_1	68.8	70.88	63.67
K_2	107.5	99.78	-
q	0.64	0.69	
V_γ	-40.9	-40.9	-4.9
rms error for primary	3	1.29	
rms error for secondary	1.28	1.41	

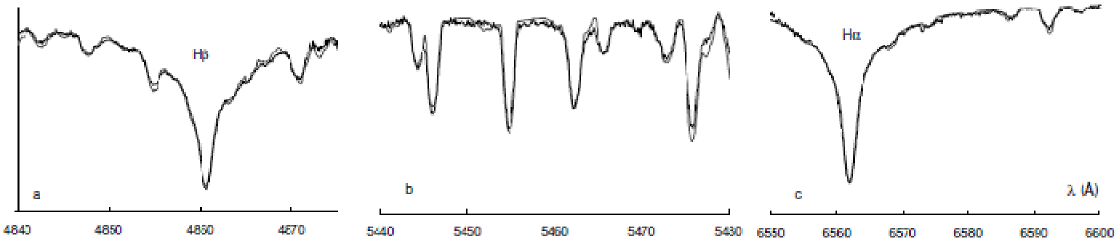

FIGURE 3. Decomposed primary component spectrum has been fitted with a model atmosphere. (a) H_β (b) 33^{rd} order and (c) H_α regions.

ACKNOWLEDGMENTS

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Setting a New Standard in the Analysis of Binary Stars
K. Pavlovski, A. Tkachenko and G. Torres (eds)
EAS Publications Series, **64** *(2013) 219–227*

SPECTROSCOPIC ANALYSIS OF ECLIPSING SB2 STARS: A CASE STUDY

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Abstract. The investigation of eclipsing spectroscopic binaries provides basic parameters of stars in a direct way. Whereas the measurable absolute masses can be used to calibrate stellar evolutionary scenarios, the effective temperatures derived from spectroscopic analysis are an important input to light curve and asteroseismic modelling. We compare different methods for investigating eclipsing SB2 stars focusing on radial velocity determination and spectrum decomposition and analysis. Used methods are the two-dimensional cross-correlation technique TODCOR, spectral disentangling with the Fourier transform-based KOREL program, and a grid search-based method of spectrum analysis using spectrum synthesis. The study is based on the investigation of two eclipsing SB2 stars observed by the *Kepler* satellite mission.

1 Introduction

The space-based, high-precision photometry by satellite missions like *CoRoT* and *Kepler* have opened a new era of accurate measurement of stellar parameters and calibration of evolutionary scenarios. Although both satellites were launched with the primary goal of searching for extrasolar planets, the long-term and almost continuous monitoring of hundreds of thousands of stars has led to the discovery of a large number of variable stars, including about 2100 eclipsing binaries (EBs) in the case of *Kepler* (Slawson *et al.* 2011). Among them are binaries with pulsating

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components for which asteroseismic analysis can provide insight into the structure of their stellar interiors.

An asteroseismic modelling analysis, on the other hand, requires accurate fundamental parameters of the stars which cannot be gathered from the single, wide-band photometry of space missions like *Kepler* alone. Ground-based multi-colour or spectroscopic follow-up observations are necessary to provide the missing colour information for deriving the temperatures of the stars. In the case of eclipsing SB2 stars, spectroscopy can deliver the radial velocity (RV) curves of the components and so the mass ratio and, in combination with the light curve (LC) analysis, the absolute masses of components.

We applied different techniques to determine the RVs of two eclipsing SB2 stars observed by *Kepler* and to decompose and analyse the spectra of the components. One of them, KIC 10661783, is an Algol-type system of extremely small mass ratio. The other star, KIC 3858884, is a δ Scuti pulsator in an EB with highly eccentric orbit. In the following, we compare the results obtained with the different methods and discuss their pros and cons.

2 KIC 10661783

2.1 *Motivation*

KIC 10661783 is a short-period ($P \sim 1.23$ d) binary star. Southworth *et al.* (2011) analysed its *Kepler* LC and found at least 68 frequencies of which 55 can be attributed to pulsation modes of the primary component. The main frequency range lies between 18 and 31 $\mathrm{c\,d^{-1}}$. The star was suspected to be a so-called oEA star (Mkrtichian *et al.* 2002), an active Algol-type system where the primary shows δ Scuti-type oscillations. Our investigation showed, however, that the star is a detached, post Algol-type system, and, it is the Algol with the smallest mass ratio observed so far. Results were published in Lehmann *et al.* (2013, Paper I).

2.2 *Analysis with* KOREL

KIC 10661783 is a SB2 star with a very faint secondary component. We used the KOREL program (Hadrava 2006) to obtain, from a time series of high-resolution ($R = 85\,000$) composite spectra taken with the HERMES spectrograph at the Mercator telescope at La Palma, the decomposed spectra of the components.

KOREL is a Fourier transform-based program for spectral disentangling. Spectral disentangling means that the shifts applied to the contributions of the two components to build the decomposed spectra are determined together with optimized orbital parameters. The program also allows computation of the temporal variation in line strengths of the components such as due to eclipses. Drawbacks concern A) the definition of the local continua of the decomposed spectra and B) the normalisation (absolute line depths) of the decomposed spectra.

Problem A) is known as the low-frequency problem in Fourier transform-based methods (*e.g.*, Hensberge *et al.* 2008) and causes undulations in the continua of

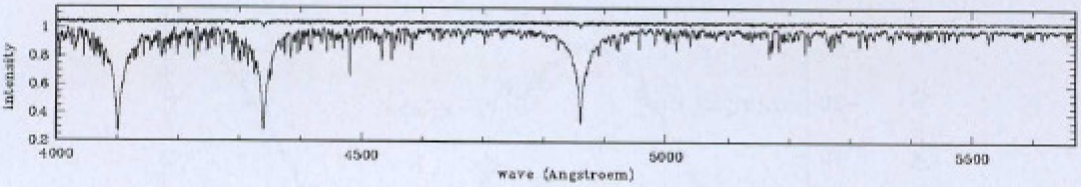

Fig. 1. Decomposed spectra of KIC 10661783 (from Paper I).

Table 1. KIC 10661783: Atmospheric parameters from spectrum analysis.

		primary	secondary
$T_{\rm eff}$	(K)	7764 ± 54	5980 ± 72
$\log g$	(cgs)	3.9 fixed	3.6 fixed
$v \sin i$	($\rm km\,s^{-1}$)	79 ± 4	48 ± 3
[Fe/H]	(dex)	-0.04 ± 0.07	-0.34 ± 0.10
$F_2/F_1(\lambda = 5000$ Å)		0.067 ± 0.003	

the decomposed spectra, mainly due to imperfections in the continuum normalisation of the observed spectra. Hensberge *et al.* (2008) showed that intrinsic light variations can stabilise the separation of the components in the KOREL method. Allowing for variable line strengths in the solution should lift the degeneracy in the determination of the local continua. This approach failed in our case: we ended up with two identical spectra scaled to different line depths. The reason was a wrong weighting of the spectra included, caused by the fact that unusually strong line depths were assigned to few spectra close to eclipse. To overcome this problem, which had not been seen before, we split the spectra into small, overlapping bins and decomposed these bins separately, based on fixed orbital elements determined from a larger wavelength range. Slight undulations in the continua were corrected using spline functions. Figure 1 shows the merged decomposed spectra. It also illustrates the faintness of the companion spectrum.

Problem B) is inherent to all methods of spectrum decomposition. The decomposed spectra are always normalised to the combined continuum flux from both components, as the observed spectra are. The renormalisation to the continuum fluxes of the individual components requires knowledge about the flux ratio between them, *e.g.*, from multi-colour photometry. Since we could not find any such photometry for our star, we tried to solve the problem by including the continuum flux ratio as a free, wavelength-dependent parameter into the analysis of the decomposed spectra. In this case, spectrum analysis has to be done on both components simultaneously. We used the method of spectrum synthesis (Lehmann *et al.* 2011), defining a χ^2 that includes the O–C values from the combined fitting of both components (see Paper I). The $\log g$ were fixed to the values obtained from LC analysis.

Table 1 lists the derived atmospheric parameters. We included all parameters into a common error analysis, accounting for all degeneracies between

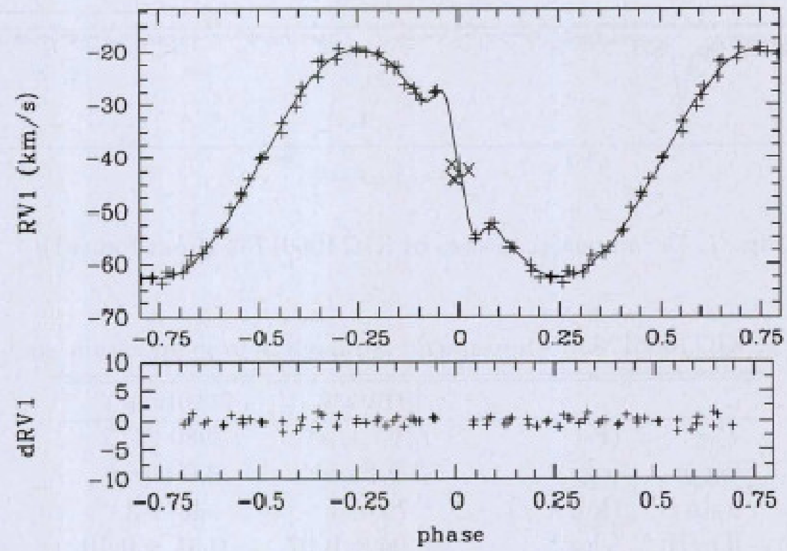

Fig. 2. RVs of the primary component (included RVs are shown by plus signs, outliers by crosses). Solid curve: calculated with PHOEBE. *Lower panel*: O–C residuals (from Paper I).

the parameters. Table 1 shows that, despite the small flux ratio of 0.067, the errors of the parameters derived for the two stars are of the same order. The assumed reason is, besides the fact that the lower-temperature companion shows a denser metal lines spectrum, that the errors are mainly determined by the degeneracy between the different parameters, in particular between $T_{\rm eff}$, $\log g$, and [Fe/H].

KOREL also delivers the orbital parameters (see Table 2 for the most important ones) and the RVs of the components in terms of the shifts applied to the spectra of the components. It does not deliver the errors of the RVs and does not consider any deviations from Keplerian orbital RVs such as caused by the Rossiter-McLaughlin effect (RME, Rossiter 1924; McLaughlin 1924). For that reason, we determined the RVs by a model-independent method using the TODCOR program.

2.3 Analysis with TODCOR

TODCOR (Mazeh & Zucker 1994) performs a two-dimensional cross-correlation between the observed, composite spectra and two different template spectra. It can also determine the flux ratio between the components. We used the best fitting synthetic spectra obtained from spectrum analysis as templates and extended the program to work on a grid of different $v \sin i$ of the templates to count for the different effective line widths due to the RME observed during the eclipses. Finally, we fitted the measured RVs and determined the orbital parameters using the PHOEBE program (Prša & Zwitter 2005).

Figure 2 shows that the RME can be perfectly fitted which was not the case when using constant $v \sin i$. Figure 3 documents that the flux ratio and effective

Table 2. Mass ratio and separation based on the KOREL and on the TODCOR RVs.

method	q	$a(R_\odot)$
KOREL	0.0909 ± 0.0011	6.31 ± 0.14
TODCOR	0.09109 ± 0.00065	6.370 ± 0.026

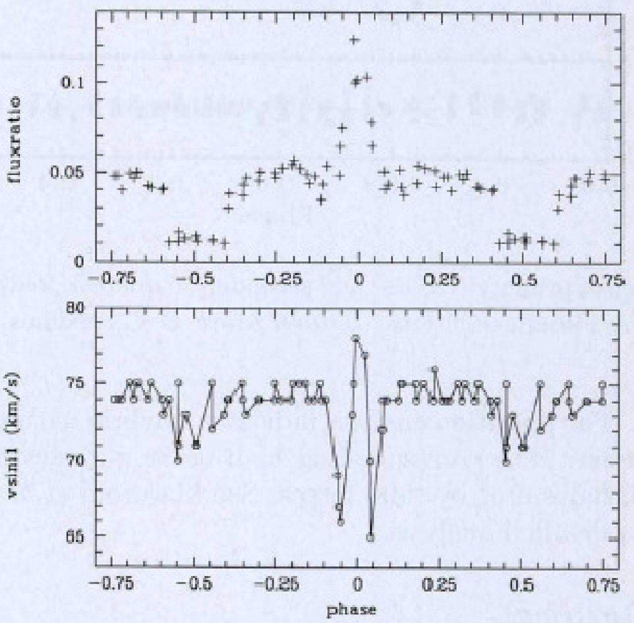

Fig. 3. Flux ratio and $v \sin i$ of the primary folded with the orbital period (from Paper I).

line width ($v \sin i$) show the expected behaviour. The flux ratio is almost zero during the (total) secondary eclipse and rises during Min I (located at phase zero). The lines get sharper during ingress and egress of Min I and reach their maximum at the centre of the (partial) eclipse. The behaviour during Min II is an artifact due to the fact that Min II is a total eclipse.

Although the usage of variable flux ratio and $v \sin i$ led to a perfect fitting of the RVs during the RME, a closer investigation showed that the absolute values of flux ratio and $v \sin i$ determined with TODCOR are not reliable and are much better constrained by the spectrum analysis. Table 2 compares the two basic parameters mass ratio and semi-major axis based on KOREL and TODCOR RVs. It can be seen that TODCOR plus PHOEBE deliver the more precise values.

3 KIC 3858884

3.1 Motivation

The *Kepler* target KIC 3858884 is an EB in a highly eccentric orbit whose LC is characterised by deep eclipses and complex periodic pulsation patterns suggesting

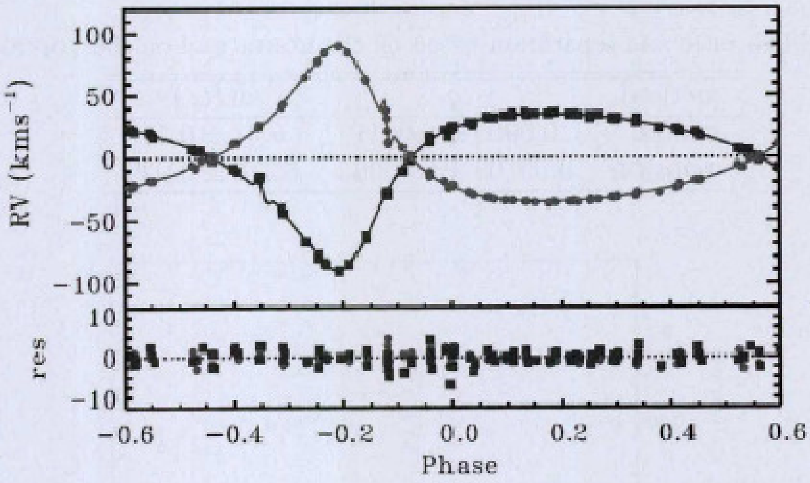

Fig. 4. KOREL-RVs of primary (circles) and secondary (squares), folded with the orbital period. *Solid curves*: PHOEBE-solutions. *Bottom panel*: O–C residuals (Paper II).

δ Scuti pulsations. The pulsation analysis indicates a hybrid nature of the pulsating secondary component. The corresponding high order g-modes might be excited by an intrinsic mechanism or by tidal forces. See Maceroni *et al.* (2013, Paper II) for the results of a detailed analysis.

3.2 Analysis with KOREL

Contrary to KIC 10661783, KIC 3858884 is an EB consisting of two components of almost the same brightness. For the decomposition with KOREL, we mainly used spectra taken with the 2m-telescope of the Thüringer Landessternwarte Tautenburg ($R = 32\,000$) and computed two solutions, one by including the spectra taken during Min I and one without these spectra. In the first solution the decomposed spectrum of the primary was broadened by the strong RME (see Fig. 4). The second solution showed undulations in the continua of both decomposed spectra which is due to the fact that no intrinsic light variation occurred anymore. Finally, we found a compromise by excluding all but two spectra taken at Min I. The decomposed spectra did not show any undulations and no difference in the line profiles compared to the exclusion of all spectra around Min I could be found. As before, we added the flux ratio as a free parameter and performed the spectrum analysis on both decomposed spectra simultaneously. The $\log g$ were fixed to the values obtained from the LC analysis. Table 3 lists the results.

3.3 Analysis with TODCOR

TODCOR was applied to the observed composite spectra and the measured RVs were fitted with PHOEBE. Both in the TODCOR and in the KOREL RVs, two dominating pulsation frequencies were found after subtracting the orbital solution. The values of these frequencies are in very good agreement with the two main frequencies

Table 3. KIC 3858884: Atmospheric parameters from spectrum analysis.

		primary	secondary
$T_{\rm eff}$	(K)	6810 ± 70	6890 ± 80
$\log g$	(cgs)	3.6 fixed	3.7 fixed
$v \sin i$	$({\rm km\,s^{-1}})$	32.2 ± 1.5	25.7 ± 1.5
[Fe/H]	(dex)	-0.09 ± 0.07	-0.26 ± 0.07
$F_2/F_1(\lambda = 5000\,\text{Å})$		0.904 ± 0.022	

Table 4. Mass ratio and separation based on the KOREL and on the TODCOR RVs.

method	q	$a(R_\odot)$
KOREL	0.9991 ± 0.0054	57.08 ± 0.16
TODCOR	0.9880 ± 0.0068	57.22 ± 0.20

found in the *Kepler* LC. Contrary to the case of KIC 10661783, TODCOR delivered more outliers in RV close to the conjunctions (phases of minimum separation in RV) than KOREL. All KOREL-based RVs could be fitted well by the PHOEBE program. Figure 4 illustrates this showing the KOREL-based orbital solution after subtracting the two mentioned pulsation frequencies. Table 4 compares the mass ratio and separation obtained with the two different methods. It can be seen that the errors from both methods are of the same order.

4 Conclusions

We applied different techniques to decompose the spectra of two eclipsing SB2 stars, to analyse their components, and to determine their orbits. Results have been used, in combination with the photometric analysis of the *Kepler* LCs, to reveal the true nature of KIC 10661783 and to derive basic stellar and system parameters of both targets as a precondition for further asteroseismic modelling (see Papers I and II).

Spectral disentangling with the KOREL program showed that obtaining smooth, undulation-free local continua of the decomposed spectra is not a straightforward task. Although the intrinsic light variation of the EBs during the eclipses should lift the degeneracy in the low-frequency range of Fourier transform, we got no reliable results for KIC 10661783 and had to split the spectra into small wavelength bins using constant line strengths. For KIC 3858884 we got a smooth solution over a large wavelength range when including two well-selected spectra taken during Min I into the disentangling. This was done as a compromise between excluding all eclipse spectra (strong undulations occur) and including all eclipse spectra (the decomposed spectral lines are broadened due to the RME).

The KOREL program delivers RVs in terms of the shifts applied to the contributions of the components to build the decomposed spectra as well as optimised orbital parameters. The solution is constrained by Keplerian motion and does not consider any deviations like the RME or proximity effects. TODCOR, on the other hand, delivers model-independent RVs that can be used with some advanced binary code like PHOEBE to model the Keplerian orbit including the RME and proximity effects. In the case of KIC 10661783 where the companion is very faint, the modelling with PHOEBE perfectly fits the RVs derived with TODCOR, including the phases around Min I where the Keplerian curve is strongly distorted by the RME. KOREL, on the other hand, gave no satisfactory RVs at these phases. The situation was inverse when analysing KIC 3858884 that has two components of almost the same brightness. Here, KOREL performed better at the conjunction phases and the RME could also be modelled very well.

In Paper I we introduced an algorithm to derive the flux ratio together with optimised stellar parameters by analysing the two KOREL-decomposed spectra simultaneously, defining a combined χ^2. The application to the two target stars showed that we can derive precise flux ratios in this way. But, due to the enlarged number of degrees of freedom, the stellar parameter errors are increased compared to the case when the flux ratio is *a priori* known and a separate analysis of the (renormalised) spectra is performed.

A necessary precondition for deriving accurate RVs with the TODCOR program during the eclipses was to allow for variable line widths (obviously well approximated by variable $v \sin i$). The variations of $v \sin i$ and flux ratio calculated in this way correspond to the expected behaviour but the absolute values derived for the out-of-eclipse phases did not agree with those derived from spectrum analysis. We conclude that TODCOR should not be used to derive accurate stellar parameters by working on a grid of different synthetic templates. As long as the used method for spectrum disentangling does not consider intrinsic deviations from pure Keplerian motion, an independent measurement of RVs using a program like TODCOR is strongly indicated, however.

This work is partly based on observations with the HERMES spectrograph operated at the Mercator telescope at La Palma. We made use of VO-KOREL, provided in the framework of the Czech Virtual Observatory (CZVO) by P. Škoda and J. Fuchs using the Fourier disentangling code KOREL by P. Hadrava. AT is a Postdoctoral Fellow of the Fund for Scientific Research (FWO), Flanders, Belgium.

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V2368 Ophiuchi: an eclipsing and double-lined spectroscopic binary used as a photometric comparison star for U Ophiuchi*,**,***

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ABSTRACT

The A-type star HR 6412 = V2368 Oph was used by several investigators as a photometric comparison star for the known eclipsing binary U Oph but was found to be variable by three independent groups, including us. By analysing series of new spectral and photometric observations and a critical compilation of available radial velocities, we were able to find the correct period of light and radial-velocity variations and demonstrate that the object is an eclipsing and double-lined spectroscopic binary moving in a highly eccentric orbit. We derived a linear ephemeris $T_{\rm min.I}$ = HJD (2 454 294.67 ± 0.01) + ($38^{\rm d}.32712 \pm 0^{\rm d}.00004$) × E and estimated preliminary basic physical properties of the binary. The dereddened *UBV* magnitudes and effective temperatures of the primary and secondary, based on our light- and velocity-curve solutions, led to distance estimates that agree with the Hipparcos distance within the errors. We find that the mass ratio must be close to one, but the limited number and wavelength range of our current spectra does not allow a truly precise determination of the binary masses. Nevertheless, our results show convincingly that both binary components are evolved away from the main sequence, which makes this system astrophysically very important. There are only a few similarly evolved A-type stars among known eclipsing binaries. Future systematic observations and careful analyses can provide very stringent tests for the stellar evolutionary theory.

Key words. stars: early-type – binaries: close – stars: individual: V2368 Oph – stars: individual: U Oph – binaries: spectroscopic

1. Introduction

HR 6412 = HD 156208 has often been used as the photometric comparison star for a well-known eclipsing binary U Oph, which exhibits apsidal motion (Huffer & Kopal 1951; Koch & Koegler 1977; Wolf et al. 2002; Vaz et al. 2007). McAlister et al. (1987) reported that HR 6412 is a speckle-interferometric binary with a separation of 0."136 and estimated the orbital period to 72 years. However, McAlister et al. (1993) could not resolve this pair and concluded that the original detection had been spurious.

In Table 1, we summarize the various determinations of the yellow magnitude of V2368 Oph published by several authors. It seems to indicate that no secular variations in its brightness have been recorded, since the scatter of values of a few hundredths of a magnitude is quite normal for yellow magnitudes recorded in different photometric systems.

Table 1. Published yellow magnitudes of V2368 Oph.

Mag.	Source	Photometric system
$6^{\rm m}.17$	Eggen (1955)	$(P,V)_E$ system
$6^{\rm m}.19$	Stokes (1972)	*uvby* and Hβ
$6^{\rm m}.16$	Becker et al. (1975)	Cousins' values
$6^{\rm m}.178$	Grønbech & Olsen (1976)	*uvby*; 1965–1970
$6^{\rm m}.177$	Sowell & Wilson (1993)	*uvby*; Nov. 1988 & Apr. 1991
$6^{\rm m}.18$	van Gent (1982)	*BVR*; 1970

During our 2001 observations of U Oph at San Pedro Mártir Observatory (SPM hereafter), HR 6412 was also used as the comparison star. We noticed large changes in this comparison on JD 2 452071.71–1.85. Upon a literature search, we found that the variability of HR 6412 has been discovered by Perryman & ESA (1997), who classified it as an eclipsing binary with a period of $7^{\rm d}.70$. Kazarovets et al. (1999) then assigned it the variable-star name V2368 Oph. The variability has also been confirmed by Vaz et al. (2007), who mention that the period found by Perryman & ESA (1997) was incorrect but give no other details.

* Based on new spectral and photometric observations from the following observatories: Dominion Astrophysical Observatory, Hvar, Ondřejov, San Pedro Mártir, Tubitak National Observatory, and ASAS service.

** Appendices are available in electronic form at http://www.aanda.org

*** Tables 2–4 are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/531/A49

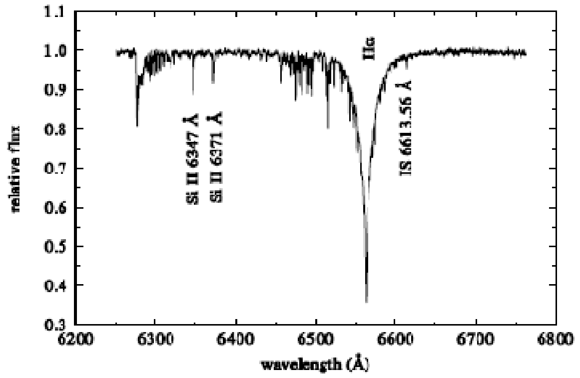

Fig. 1. One complete Ondřejov red spectrum of V2368 Oph, taken on HJD 2454357.2917, which shows that the only stronger lines, suitable for the RV measurements, are Hα and the SiII 6347 and 6371 Å. The spectrum contains many water vapour and oxygen telluric lines and the interstellar line at 6613.56 Å.

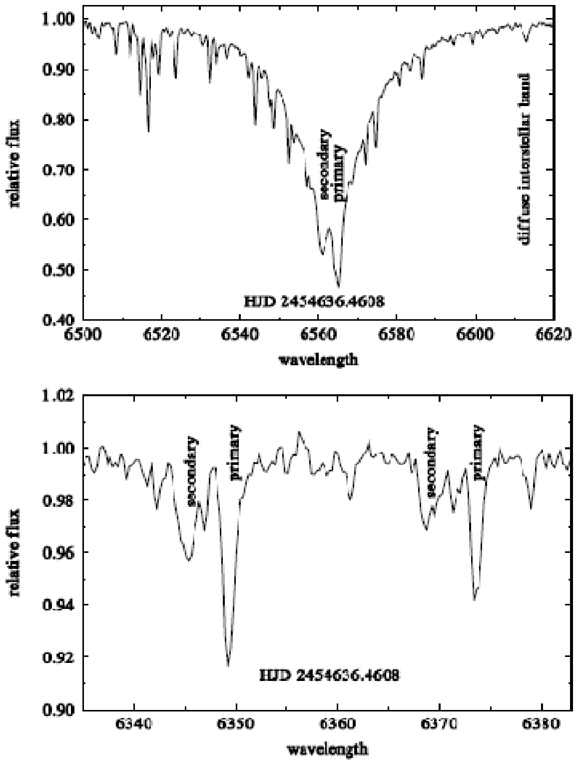

Fig. 2. The Hα and SiII 6347 and 6371 Å line profiles from the Ondřejov spectrum taken near one periastron passage on HJD 2 454 636.4608. One can clearly see the lines of both binary components, separated by more than 200 km s^{-1} in their radial velocity.

The main goal of this study is to publish the first correct and accurate linear ephemeris of V2368 Oph, which can be used to correct earlier photometric observations of U Oph. We also derive preliminary orbital and light-curve solutions and show that they can lead to self consistent basic physical properties of the binary. However, considering the limited amount and heterogeneity of our observational material, we do not aim to determine the final, accurate physical elements of the system.

2. Observational material used

2.1. Photometry

After realising that V2368 Oph is a variable star, we started systematic *UBV* observations of it at Hvar and SPM observatories. A limited set of *UBV* observations was also obtained by HA at the Turkish National Observatory. Besides, we compiled the Hipparcos H_p observations and *V* photometry from the ASAS project (Pojmanski 2002). Details on data sets and their reduction are in Appendix A, and all individual *UBV* and *V* observations with their HJDs are provided in Table 2 (available at the CDS).

2.2. Spectroscopy

Simultaneously with photometric observations, we also begun to collect electronic spectra in Ondřejov, San Pedro Mártir, and Dominion Astrophysical Observatory (OND, SPM, and DAO hereafter). A detailed discussion of all spectra, their reduction, and a journal of observations can be found in Appendix B.

Here, we only want to add a few comments relevant to further analyses. The only spectral region that is available in the spectra from all three observatories is the red region containing only three strong enough spectral lines suitable for the RV measurements: the Balmer Hα line and the doublet of SiII 6347 and 6371 Å lines (see Figs. 1 and 2). The SPM spectra also cover the region of MgII 4481 Å line, in which both components are clearly seen, so this line was also found suitable for the RV measurements. The RV measurements were carried out in three different ways. (1) We used the program SPEFO (Horn et al. 1996; Škoda 1996), which permits the RV measurements via sliding direct and flipped line profiles on the computer screen until a perfect match is obtained. (2) We fitted the observed line profiles by two Gaussians shifted in their positions in such a way as to obtain the best match of the observed, often blended line profiles of the primary and secondary. (3) We verified our RV values by an automated fitting of a combination of two synthetic spectra – selected from the Ondřejov library of synthetic spectra, prepared and freely distributed by Dr. J. Kubát – to each of the observed spectra using a simplex algorithm. The χ^2 (defined in Brož et al. 2010) was calculated for the *entire* red spectrum in the wave length range 6256 to 6768 Å, which includes all the individual lines analysed previously.

The second method is preferred as it returns the most likely velocity amplitudes. The results of the third method are statistically compatible. The first method (SPEFO RV measurements) usually underestimates the true semi-amplitudes of the orbital motion, because of the line blending, especially for the steep wings of Hα. We, therefore, used the SPEFO Hα RVs only for the initial search of the orbital period, to combine them with older published RVs, measured in a standard way from the photographic spectra.

For all red spectra, we followed the procedure outlined in Horn et al. (1996) and measured RVs of a selection of unblended *telluric* lines in SPEFO. We then used the difference between the calculated heliocentric RV correction and the true mean RV of telluric lines to correct the zero point of the RV scale individually for each spectrogram. Regrettably, these corrections were

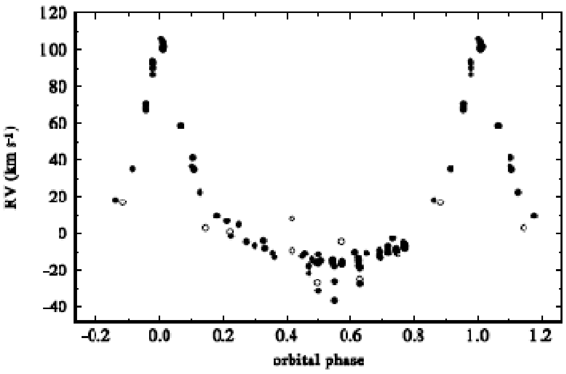

Fig. 3. The radial-velocity curve of the primary component of V2368 Oph based on Hα RVs measured in SPEFO for our OND, DAO, and SPM spectra (filled circles) and published RVs (open circles) for the period of $38^{\rm d}3307$ from the FOTEL orbital solution with phase zero at periastron passage. See the text for details.

less reliable for the majority of the red SPM spectra, which only contain very weak telluric lines owing to the high altitude of that observatory. No such corrections were possible for the blue SPM spectra in the absence of telluric lines, of course.

Individual Hα, SiII, and MgII RVs, measured in a standard way in SPEFO and via Gaussian fits to line profiles with their HJDs of mid-exposures are in Table 3 (available at the CDS). The rectified and wavelength-calibrated spectra are in Table 4 (available at the CDS).

3. Preliminary analysis and search for a correct orbital period

As our observations progressed, it soon became obvious that the orbital period must be much longer than the $7^{\rm d}70$ period reported by Perryman & ESA (1997) and that the orbit had to have a high eccentricity, since we were observing a constant brightness and only small RV changes. When we finally succeeded in observing a decline into the minimum on the night JD 2 454 294.35-4.54, we were able to combine it with earlier minima recorded by Hipparcos, ASAS, and our discovery observation at SPM and to obtain the first guess that the period should be close to 38 days. Continuing spectroscopic observations then allowed us to cover parts of two periastron passages on JD 2 454 366-67, and JD 2 454 636 and an iterative analyses of the RV and light curves allowed us to estimate the value of the orbital period to $38^{\rm d}33$.

There are two limited sets of earlier RV measurements. Christie (1925) published five RVs covering the interval JD 2 423 233.8–995.8, and Palmer et al. (1968) published another five RVs from low-dispersion spectra covering JD 2 437 441.6-740.7. We combined these RVs with our own RV measurements in the program SPEFO (Horn et al. 1996; Škoda 1996) for the Hα line and used the FOTEL program (Hadrava 1990, 2004a) to derive preliminary orbital elements and a more accurate value of the period. We obtained $P = 38^{\rm d}3302 \pm 0^{\rm d}0015$, $T_{\rm periast.}$ = HJD 54 290.894 + 0.096, $T_{\rm min\,I}$ = HJD 54 294.417, $e = 0.551 \pm 0.010$, $\omega = 355.2 \pm 1.6$, $K_1 = 59.71 \pm 4.1$ km s^{-1}, $\gamma_{\rm old} = 17.0 \pm 3.4$, and $\gamma_{\rm new} = 10.07 \pm 0.50$, the rms errors of the model fit to the data per 1 observation being 10.3, and 4.1 km s^{-1} for the old and new RVs.

Since the narrow and steep photometric eclipses are very sensitive to the phase shifts, we used an interactive computer program (written by HB), which allows the user to display the phase diagrams based on the observed data in the neighbourhood of the eclipses for various smoothly varied values of the orbital period. This way we found that the true orbital period must be very close to the value of $38^{\rm d}3272$.

4. Towards basic physical properties of the binary

To obtain self-consistent physical properties of the components and the binary system, we had to proceed in an iterative way. We selected several stronger lines seen in both binary components and derived their RVs via Gaussian fits to line profiles. In particular, we used the SiII 6347&6371 Å and Hα lines, available in all spectra, and MgII 4481 Å, measurable in the SPM spectra. For Hα, the Gaussian profiles were not optimal so we tentatively disentangled the Hα profiles, using the KOREL program (Hadrava 1995, 1997, 2004b, 2005) and used the disentangled profiles instead of Gaussians[1].

We alternatively used the programs PHOEBE (Prša & Zwitter 2005, 2006) based on the Wilson & Devinney (1971) program, and FOTEL, already used in the first step, to derive preliminary values of some critical parameters. To obtain the best possible estimate of the RV semi-amplitudes, we allowed for individual systemic velocities for each of the ions used. In particular, we found the systemic velocities of 2.97 ± 0.55, 0.14 ± 0.54, and 9.9 ± 6.0 for SiII, MgII, and Hα, respectively. The differences between these values are probably insignificant considering their errors and the inability to check the zero point of the RV scale for the blue spectra via measurements of the telluric lines. Since PHOEBE can treat only one joint systemic velocity, we subtracted the values of respective systemic velocities from the observed RVs and used these shifted RVs from all three ions as one dataset for the primary and another one for the secondary in PHOEBE. We then naturally kept the systemic velocity fixed at zero in PHOEBE solutions.

In the latest (development) version of PHOEBE that we are using, the convergence is governed by minimization of a cost function χ^2 defined in the case of our datasets as

$$\chi^2 = \sum_p \frac{1}{\sigma_p^2} \sum_{i=1}^{N_p} w_i (f_i - s_i)^2, \quad (1)$$

where index p denotes the individual photometric passbands, σ_p their standard deviations per 1 observation, N_p is the number of individual observations for pth passband, w_i are standard weights of individual observations, and f_i and s_i the observed and calculated fluxes, respectively. The value of the χ^2 function is tabulated along with the solutions.

Although it should be possible to derive the effective temperatures of both binary components from calibrated UBV photometry (Prša & Zwitter 2006; Wilson 2008), the propagation of errors often leads to unreliable results. For that reason we restricted ourselves to the standard approach of estimating the effective temperature of the primary from the dereddened colours and observed spectra, then keeping its value fixed in the solutions.

[1] It would seem logical to derive the orbital solution directly with KOREL. However, due to heterogeneity of the available spectra, their different spectral resolutions and relatively limited number, this procedure was not satisfactory in the given case.

Table 5. Published *uvby* and Hβ observations of V2368 Oph.

V	$b-y$	m_1	c_1	N_{uvby}	Hβ	$N_{H\beta}$	Source
–	0ᵐ167	0ᵐ090	1ᵐ195	5	2.850	4	Crawford et al. (1972)
6ᵐ19	0ᵐ177	0ᵐ095	1ᵐ216	3	2.860	3	Stokes (1972)
6ᵐ178(1)	0ᵐ161(2)	0ᵐ095(2)	1ᵐ204(2)	2	–		Grønbech & Olsen (1976)
–	–	–	–		2.870(2)	3	Grønbech et al. (1977)
6ᵐ177(5)	0ᵐ189(2)	0ᵐ072(5)	1ᵐ203(5)	3			Sowell & Wilson (1993)

Table 6. The final combined light-curve and RV-curve solutions obtained with PHOEBE.

Element		Primary	Binary	Secondary	Primary	Binary	Secondary
P	(d)		38.327115(43)			38.327118(43)	
$T_{\rm periastr.}$	(RJD)		54291.039(11)			54291.042(11)	
$T_{\rm min.I}$	(RJD)		54294.670(17)			54294.668(17)	
$T_{\rm min.II}$	(RJD)		54287.498(17)			54287.495(17)	
e			0.51527(14)			0.51524(14)	
ω	(°)		359.33(20)			359.41(20)	
i	(°)		86.165(22)			86.139(22)	
r		0.0473		0.0460	0.0477		0.0464
Ω		23.29(11)		24.75(12)	23.05(11)		23.71(11)
a	$(R_\odot)$		83.67(67)			83.70(68)	
K_j	(km s^{-1})	65.7(8)		62.9(9)	64.3(6)		64.3(6)
K_2/K_1			1.044(15)			1.0 fixed	
$T_{\rm eff}$	(K)	9300 fixed		9500(200)	9300 fixed		9500(200)
M	$(M_\odot)$	2.62(2)		2.74(7)	2.68(8)		2.68(8)
R	$(R_\odot)$	3.96(2)		3.84(2)	3.99(3)		3.87(2)
$M_{\rm bol}$	(mag)	−0.31(9)		−0.34(9)	−0.33(9)		−0.36(9)
log g	[cgs]	3.66(1)		3.71(1)	3.66(3)		3.69(3)
L_j	V band	0.5029(30)		0.4971	0.5024(30)		0.4976
L_j	B band	0.5004(32)		0.4996	0.4995(32)		0.5005
L_j	U band	0.4942(37)		0.5058	0.4927(38)		0.5073
V	(mag)	6.913(16)	6.167(11)	6.926(16)	6.913(16)	6.166(11)	6.924(16)
B	(mag)	7.137(17)	6.386(11)	7.139(17)	7.139(17)	6.385(11)	7.137(17)
U	(mag)	7.363(20)	6.598(13)	7.338(20)	7.367(20)	6.599(13)	7.335(20)
V_0	(mag)	6.26(8)		6.29(8)	6.26(8)		6.29(8)
$(B-V)_0$	(mag)	0.021(11)		0.014(11)	0.021(11)		0.014(11)
$(U-B)_0$	(mag)	0.077(15)		0.054(15)	0.078(15)		0.053(15)
No. of obs.	UBV/RV		1913 / 268			1913 /268	
χ^2			1726			1730	

Notes. Columns 2–4 contain a solution based on the free convergence; Cols 5–7 contain the solution for the fixed mass ratio of 1. All epochs are in RJD = HJD − 2 400 000. Probable elements and their formal error estimates are provided, where Ω is the value of the Roche-model potential used in the WD program, and L_j ($j = 1, 2$) are the relative luminosities of the components in individual photometric passbands. They are normalized so that $L_1 + L_2 = 1$. The number of observations represents the sum of RVs of the primary and secondary and a sum of individual observations in all passbands.

There are four sets of *uvby* observations and three sets of Hβ photometry of V2368 Oph – see Table 5. Using the program UVBYBETA written by T. T. Moon and modified by R. Napiwotzki, which is based on a calibration devised by Moon & Dworetsky (1985), we found that those sets of Strömgren photometry imply a mean effective temperature of the binary between 8900 K and 9400 K and a mean log g between 3.50 and 3.61.

Since both stars are detached well even near periastron, the light-curve solution basically does not depend on the exact value of the mass ratio. Considering this, a preliminary PHOEBE solution was used to derive relative luminosities of both components. *UBV* magnitudes of the binary at maximum light from the *UBV* observations transformed to the standard system and from them the *UBV* magnitudes of the primary and secondary in each passband. These were then dereddened in a standard way, assuming $A_V = 3.2\,E(B-V)$. The dereddened magnitudes and indices confirmed the spectral type of A2 for the primary. Using Flower (1996) calibration of $(B-V)_0$ indices vs. bolometric corrections and $T_{\rm eff}$, we estimated the effective temperature of the primary to (9300 ± 200) K. Keeping the value of 9300 K fixed, we derived a freely converged PHOEBE solution, which is presented in detail in Table 6. The rms errors of all converged parameters in PHOEBE are derived from a covariance matrix. For other, deduced parameters, we propagated the errors to obtain the estimates given in the Table. Since a realistic error of the effective temperature of the primary is about ±200 K, this must imply that the formal error of the effective temperature of the secondary, estimated from a covariance matrix in PHOEBE, is too low and must also be about ±200 K.

It is clear at first sight that this solution is not satisfactory since it leads to a model in which the more massive component is the less evolved of the two. We believe that the problem lies in the limited quality of our radial velocities. As a matter of fact, the solutions for RVs of individual ions oscillated between 0.95 and 1.05 in the resulting mass ratio. At the same time, since both binary components are well detached, the light curve solution is stable and basically does not depend on the mass ratio.

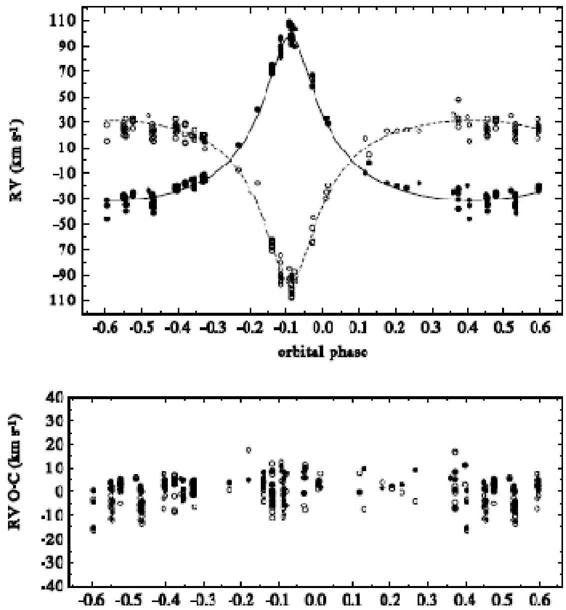

Fig. 4. The final radial-velocity curves of both binary components of V2368 Oph based on Gaussian fits (circles) and the theoretical RV curves based on our PHOEBE solution (lines). The lower panel shows the O−C residua from the solution. Typical observational uncertainties are 10 km s^{-1}. Orbital phases from ephemeris (2) are used.

Therefore, we derived another PHOEBE solution, this time with the mass ratio fixed to 1.0. This solution is also provided in the last three columns of Table 6 and we take it as the reference solution for the following discussion. The corresponding RV curves and the light curve in the V band are shown in Figs. 4, and 5, respectively. It is seen that there is little difference in all parameters, which do not depend on the mass ratio between the two solutions. For completeness, we also derived another solution for the mass ratio of 0.95. This led to a slightly worse $\chi^2 = 1770$, but the photometric elements were again very similar to those two shown in Table 6.

The solutions led to the following linear ephemeris, which should enable correction of existing photometric observations of U Oph secured differentially relative to V2368 Oph:

$$T_{\rm min.I} = \text{HJD } 2\,454\,294.67 + 38\overset{\rm d}{.}32712 \times E. \quad (2)$$

It is encouraging to note that a separate dereddening of the UBV magnitudes of the primary and secondary led invariably to $E(B-V) = 0\overset{\rm m}{.}20$ and to distance moduli of 6.46(12), and 6.47(12) for the primary and secondary, respectively. The dereddened values of the secondary indicate a slightly earlier spectral type, in accordance with its higher effective temperature obtained from the PHOEBE solution. We note that $E(b-y)$ derived with the program UVBYBETA from the $uvby$ values of Table 5 is $0\overset{\rm m}{.}15$, which agrees well with the $E(B-V)$ derived by us[2].

The parallax of V2368 Oph was obtained by the ESA Hipparcos mission, and its originally published value (Perryman & ESA 1997) is $0\overset{''}{.}00554 \pm 0\overset{''}{.}00086$, while an improved value obtained by van Leeuwen (2007a,b) reads as $0\overset{''}{.}00455 \pm 0\overset{''}{.}00048$. The distance modulus obtained from our photometric solution implies a parallax of $0\overset{''}{.}00506$, in excellent agreement with the above values, deduced from the Hipparcos observations.

[2] Note that $E(b-y) = 0.74E(B-V)$.

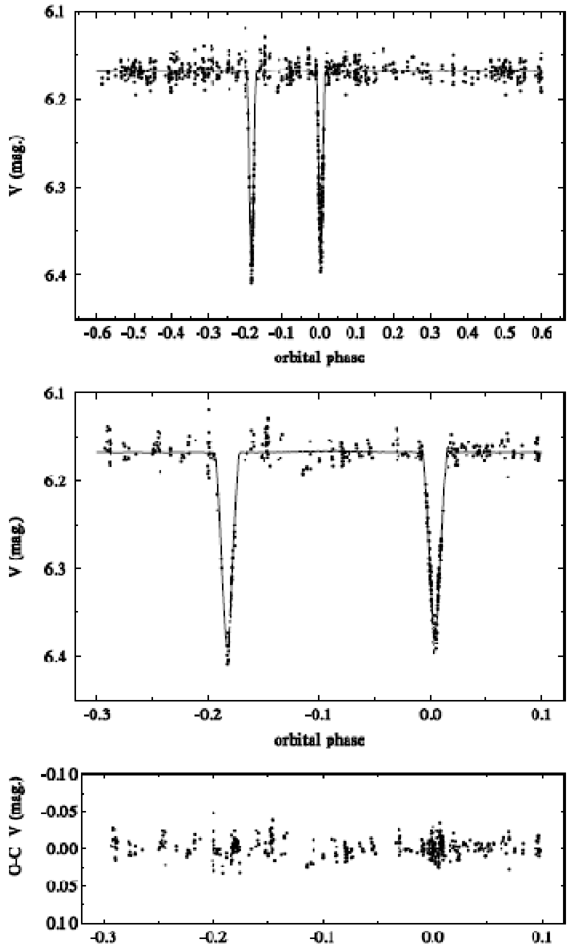

Fig. 5. The observed V-band light curve compared to the theoretical one, based on our PHOEBE solution. The lower panels show a zoom of the curves in the neighbourhood of both binary eclipses and the O−C residua from the model fit. Typical 1-σ observational uncertainties are $0\overset{\rm m}{.}01$. Orbital phases from ephemeris (2) are used.

5. Stellar evolution of the components

Since V2368 Oph is a detached binary with no evidence of mass transfer, one can use a one-dimensional program for stellar evolution to see whether the observed properties of the binary agree with the model prediction. To this end, we used the stellar-evolution module MESAstar by Paxton et al. (2011).

We first calculated the model evolution for the masses $M_1 = 2.62\,M_\odot$ and $M_2 = 2.74\,M_\odot$ which follow from the free PHOEBE solution with the lowest χ^2 for the combined photometric and RV data (Table 6, left). We assumed the same metallicities of $Z = 0.02$ for both components, of course, the helium abundance $Y = 0.28$ and the mixing-length parameter $\alpha = 2.0$. The result is compared to the observed binary properties in the Hertzsprung–Russell diagram, and the $T_{\rm eff}$ vs. radius diagram

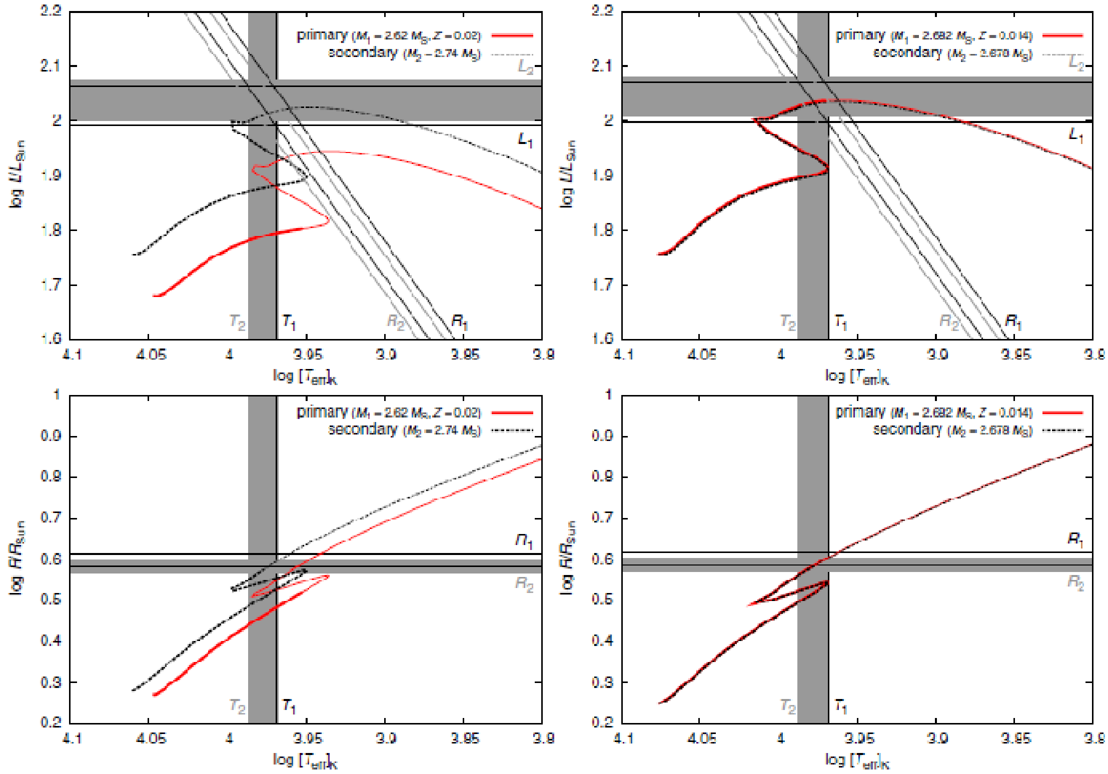

Fig. 6. *Left panels*: a Hertzsprung-Russel diagram (*top*), and the $T_{\rm eff}$ vs. radius diagram (*bottom*) showing the stellar evolution of the primary and secondary components of V2368 Oph. It was computed with the MESAstar module, for the masses $M_1 = 2.62\,M_\odot$, $M_2 = 2.74\,M_\odot$ and for the metallicity $Z = 0.02$. The evolutionary tracks are plotted by thick lines from ZAMS up to the age 3.877×10^8 y. The ranges in temperatures T_1, T_2, luminosities L_1, L_2 and radii R_1, R_2 inferred from photometry/spectroscopy are denoted by lines (refer to Table 6). There is a strong disagreement between the observations and the stellar evolution, especially for the primary. *Right panel*: same for the masses $M_1 = 2.682\,M_\odot$, $M_2 = 2.678\,M_\odot$ (i.e., the mass ratio very close to one), and a different value of the metallicity $Z = 0.014$. The thick lines are terminated at the age 3.938×10^8 y.

(Fig. 6, left panels). Even though there are uncertainties in temperatures, luminosities and masses of the individual components (refer to Table 6), their *differences* are established much more accurately; e.g., the difference in temperatures $T_2 - T_1 \simeq 200$ K is always present in PHOEBE solutions since this is enforced by the observed light curve and colour indices.

There is a clear disagreement between the photometric/spectroscopic observations and the predicted stellar evolution in this case. Since the mass ratio $q = M_1/M_2 \doteq 0.96$ differs significantly from 1, the calculated luminosities of the components are *always* very different owing to a strong dependence of the stellar evolution on the mass ($\log L_2/L_\odot$ reaches ~2.0 and $\log L_1/L_\odot \simeq 1.9$), while the observed luminosities are rather similar ($\log L_1/L_\odot \simeq \log L_2/L_\odot \simeq 2.03$). A change in neither metallicity nor in the mixing-length parameter could alter this result since a different value of Z would shift both tracks in the same direction, and varying α from 1.5 to 2.5 does not alter evolutionary tracks significantly before the red giant branch is reached.

As a second test, we took the mass ratio q close to 1, which is still compatible with the photometric/spectroscopic observations from a statistical point of view (Table 5, right). Because the stellar evolution is very sensitive to the stellar mass, we may actually use this approach to constrain the mass ratio of V2368 Oph. The most sensitive indicator seems to be the temperature – there is approximately a 200 K difference between T_1 and T_2, which corresponds to a 0.004 to 0.008 $M_\odot$ difference between M_1 and M_2, according to our tests. If we use $M_1 = 2.682\,M_\odot$ and $M_2 = 2.678\,M_\odot$ we also have to decrease the metallicity to $Z = 0.014$, which shifts both the evolutionary tracks towards higher T and L, in order to match the observed state of V2368 Oph (Fig. 6, right panels). Another possibility would be to slightly increase the masses to $M_1 = 2.760\,M_\odot$ and $M_2 = 2.752\,M_\odot$ and to retain the $Z = 0.02$ value. To conclude, it is possible to find a consistent solution for the available photometry and spectroscopy and the stellar evolution, even though the parameters presented above cannot be considered as final, because the total mass of the system is not yet constrained precisely enough.

From the standpoint of stellar evolution, V2368 Oph is a very interesting evolved system with both components leaving the main sequence. It is in a rapid phase of evolution and consequently may serve as a very sensitive test case for the stellar-evolution programmes, provided new, accurate RVs and photometric observations are acquired. Considering the relatively short distance of the binary from us, its interferometry would also be of utmost importance, providing the angular separation of the components and orbital inclination, consequently a

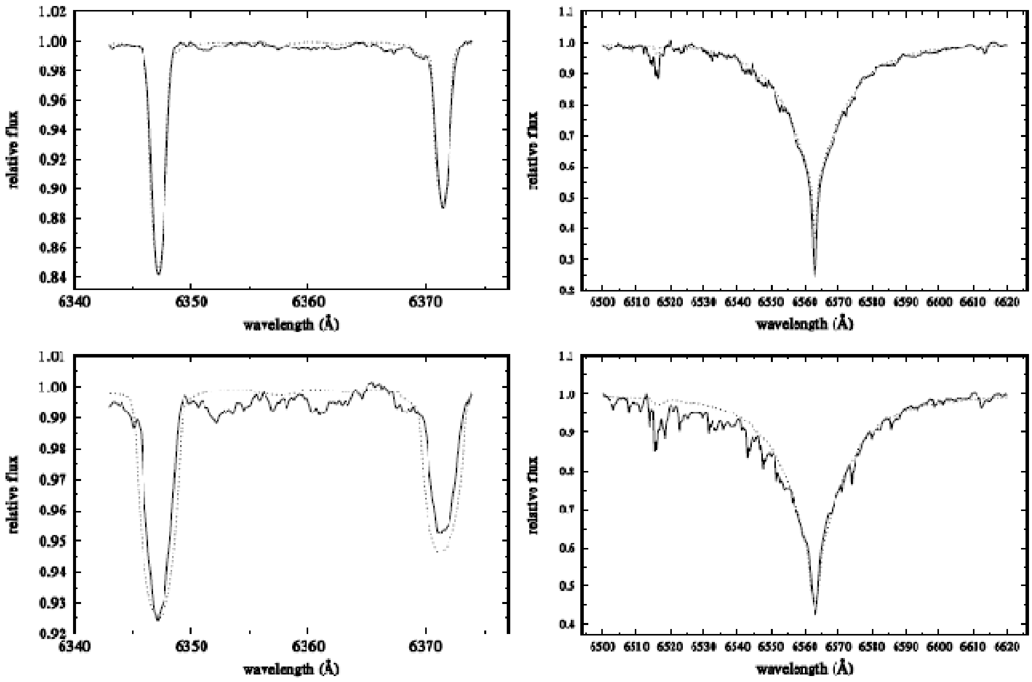

Fig. 7. A comparison of *disentangled* (solid lines) and synthetic (dotted lines) profiles of the SiII line (*left panels*) and Hα line (*right*) for the primary (*top panels*) and secondary components (*bottom*). See the text for details.

much more precise parallax and the total mass of the system. Interferometry can also provide independent constraints on the component radii.

6. A comparison with synthetic spectra and the rotation of the binary components

As another consistency check, we disentangled the SiII and Hα line profiles with the help of the KOREL program (Hadrava 1995, 1997, 2004b, 2005), keeping the orbital parameters from the second PHOEBE solution fixed, but using the mass ratio of 0.998 (considering the discussion above). In Fig. 7, the disentangled line profiles, normalized to their individual continua using the relative luminosities derived by PHOEBE, are compared with the synthetic line profiles from the Ondřejov library of synthetic spectra prepared and freely distributed by Dr. J. Kubát – see, e.g. Harmanec et al. (1997a) for details. We used the synthetic spectra for the parameters close to the PHOEBE results, namely $T_{\rm eff}$ = 9500 K and $\log g = 3.5$, rotationally broadened in SPEFO to 40 km s^{-1} for the primary and to 90 km s^{-1} for the secondary. Varying these values for more than ±5 km s^{-1} would result in a significant disagreement in the depths and widths between the observed and synthetic line profiles.

The agreement between the observed and synthetic spectra is satisfactory, lending some credibility to our result. We warn, however, that the heterogeneity of our material means that there can still be rather large uncertainties in the derived masses, radii, and luminosities. Another study based on rich and homogeneous observational material is therefore desirable.

Taken at face value, the observed projected rotational velocities and the PHOEBE solution would imply the stellar rotational periods of $5\overset{d}{.}0$ and $2\overset{d}{.}2$ for the primary and secondary, respectively, while the spin-orbit synchronization in periastron would imply a rotational period of $10\overset{d}{.}5$. It is notable that in their detailed study of another evolved A-type binary with eccentric orbit, θ^2 Tau, Torres et al. (2011) also found the projected rotational velocity for the secondary roughly twice as high as for the primary.

In passing, we wish to mention that it is also possible to make a theoretical prediction of the internal structure constant based on the current evolutionary models of Claret (2004) with the standard chemical composition of $(X, Z) = (0.70, 0.02)$: $\log k_2 = -2.498$ for both binary components. Taking the values of the eccentricity and fractional radii from Table 6 into account, we can predict a very slow apsidal-motion rate of $\dot{\omega}_{\rm obs}$ = 0.00028 deg/cycle, which is only 0.27 deg/century. The relativistic contribution to the apsidal motion is substantial: $\dot{\omega}_{\rm rel}$ = 0.00020 deg/cycle or about 70% of the total apsidal-advance rate (Gimenez 1985). In other words, there is little chance of detecting a measurable apsidal motion for this binary in the foreseeable future.

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Appendix A: Photometry

Here we provide detailed comments on the photometric observations used in this study and the way we treated them.

1. Hvar observations were secured in 2007, 2008, and 2009 and reduced and transformed into the standard *UBV* system with the HEC22 release 16.1 reduction program via nonlinear transformation formulæ (Harmanec et al. 1994; Harmanec & Horn 1998). This recent version of the program allows modelling of variable extinction during the observing night, which significantly improves the accuracy of the observations. The typical rms errors of the multinight fit to all standard stars used to define the transformation formulæ in a given observing season are $0\overset{m}{.}008$ for V and B, and $0\overset{m}{.}010$ for U. This is similar for observations from other observing stations reduced with the help of HEC22.
2. San Pedro Mártir observations were collected during the observational runs in 2001–2003 and 2007. Observations were reduced and transformed into the standard *UBV* system with the HEC22 release 14.1 reduction program via nonlinear transformation formulæ (Harmanec et al. 1994; Harmanec & Horn 1998). At that station V2368 Oph was used in 2001 as a recommended comparison star for the eclipsing binary U Oph and its magnitude difference relative to several comparison stars (HD 183324, HD 187458, HD 161132, HD 153808, and HD 144206) was derived. For all these stars, save HD 183324, the magnitudes and colours are well established from the calibrated Hvar all-sky photometry. HD 183324 = V1431 Aql was found to be a small-amplitude λ Bootis variable (Kuschnig et al. 1994). It served for a long time as a comparison star for observations of V923 Aql and V1294 Aql in the Photometry of the Bright Northern Be Star Programme (Harmanec et al. 1982, 1994; Pavlovski et al. 1997; Harmanec et al. 1997b) and its variability on longer time scales is safely excluded by numerous Hvar observations. The mean all-sky *UBV* magnitudes of HD 183324 are accurately derived. It was actually used as a comparison for V2368 Oph only on the night JD 2 452 065, and we feel that its 2 mmag microvariability is not critical for the purpose of this study. For 13 observations secured on JD 2 452 071 (when we recorded the first eclipse of V2368 Oph), it was not possible to derive the differential values for it so we adopted its all-sky values instead, since enough standard stars had been observed during the night, and the nightly transformation coefficients (extinction and its variations and the zero points) could be derived. As soon as we realized that V2368 Oph is a variable, its subsequent observations in 2002 and 2003 were carried out differentially, relative to HD 154660 = HR 6361. This A9V star is a visual binary ADS 10347A with a close companion ADS 10347B at $20\overset{''}{.}3$, which is some $3\overset{m}{.}35$ fainter than ADS 10347A. The 2007 observations were obtained with a larger diaphragm so that the light of the visual component ADS 10347B was recorded with the brighter component ADS 10347A = HD 6361. We carried out dedicated observations at Hvar to derive the total magnitude of both visual components and added this value to the magnitude differences var – comp. from this season. In all other instances, observations were carried out in such a way as to keep ADS 10347B outside the diaphragm.
3. Hipparcos all-sky H_p broad-band magnitudes secured between 1989 and 1993 (Perryman & ESA 1997) were transformed to the standard Johnson V magnitude with the nonlinear transformation formula derived by Harmanec (1998). The rms error of the fit per 1 observations is $0\overset{m}{.}0067$. For the solutions, the transmission and the limb darkening coefficients for the H_p passband were considered, however. All data with error flags larger than 1 and one deviating point at HJD 2448661.4682 were omitted.
4. TNO (Tubitak National Observatory) observations were secured during two consecutive nights in 2003 and were reduced and transformed into the standard *UBV* system with the HEC22 release 14.1 reduction program via nonlinear transformation formulæ (Harmanec et al. 1994; Harmanec & Horn 1998).
5. ASAS V magnitude observations were extracted from the public ASAS database (Pojmanski 2002); we used the data from the diaphragm, which gives the smallest rms errors and omitted a few clearly deviating data points.

The journal of all photometric observations is in Table A.1. Homogenized *UBV* magnitudes of all comparison and check stars used can be found in Table A.2.

Appendix B: Spectroscopy

The journal of all spectroscopic observations can be found in Table B.1. The individual data files are identified there by letters. Below, we provide a few comments on them.

- *File A.* CCD spectra of V2368 Oph covering the wavelength region 6260–6750 Å. They were secured with a SITe-005 800 × 2000 CCD detector attached to the medium 0.7-m camera of the coudé focus of the Ondřejov 2.0 m telescope (OND). The spectra were obtained between June 2007 and June 2008 and have a linear dispersion of 17.2 Å mm^{-1} (red) and a 2-pixel resolving power of about 12600 (11–12 km s^{-1} per pixel). Their S/N ranges from 50 (1 spectrum) to 370, and the majority have S/N over 200.
- *File B.* CCD spectra covering the wavelength region 6150–6750 Å with a resolution of 6.6 km s^{-1} per pixel. They were obtained at the DAO 1.22-m telescope between August 2007 and September 2009 and have a reciprocal linear dispersion of 10 Å mm^{-1}. The detector used was a SITe-4 4096 × 2048 CCD, and the 3-pixel resolving power was about 15 000. Their S/N ranges from 100 to 370.
- *File C.* CCD echelle spectra secured with the 2.14-m reflector of the SPM observatory in April 2003. The CCD detector has 1024 × 1024 pixels, and the setting used covered the wavelength region from 4000 to 6700 Å in grating orders 33 to 60. The nominal resolution of the spectrograph is 18 000 at 5000 Å, which translates into 2-pixel resolution of about 17 km s^{-1}.
- *File D.* Another set of echelle CCD spectra from SPM, secured in April 2007.
- *File E.* The third set of echelle CCD spectra from SPM, secured from May 30 to June 1, 2007. The S/N of the SPM spectra ranges between 120 and 500 for the red, and 85 to 230 for the blue parts of the spectra.

The initial reductions of the DAO spectra (bias subtraction, flat-fielding and conversion to 1-D images) were carried out by SY in IRAF. The initial reduction of the SPM and OND spectra was carried out by PE and by Dr. M. Šlechta, respectively, including the wavelength calibration. The remaining reductions of all spectra (including wavelength calibration for the DAO spectra, continuum rectification, and removal of cosmics and flaws) was carried out with the program SPEFO (Horn et al. 1996; Škoda 1996).

Table A.1. Journal of available photometry of V2368 Oph.

Station	Time interval (HJD−2 400 000)	No. of obs.	Passbands	HD of comparison /check star	Source
1	542 73.4–550 61.4	423	*UBV*	154660/154895	this paper
30	520 65.8–542 76.8	152	*UBV*	*)	this paper
66	527 65.4–527 66.6	10	*UBV*	154660/154895, 154445	this paper
61	479 12.6–490 61.9	111	*V*	all-sky	Perryman & ESA (1997)
93	530 55.9–532 90.5	47	*V*	all-sky	Pojmanski (2002)

Notes. Individual observing stations are distinguished by running numbers they have in the Prague/Zagreb photometric archives – see column "*Station*": 01 … Hvar 0.65-m, Cassegrain reflector, EMI9789QB tube; 30 … San Pedro Mártir, 0.84-m reflector, Cuenta-pulsos photometer; 61 … Hipparcos all-sky H_p photometry transformed to Johnson V; 66 … TNO 0.40-m Cassegrain reflector, SSP5A photometer; 93 … ASAS data archive (Pojmanski 2002). *) All-sky photometry or differential photometry relative to various comparisons during the first season when V2368 Oph was used as a comparison for observations of U Oph, then relative to HD 154660 – see the text for details.

Table A.2. Comparisons and check stars of V2368 Oph.

HD/BD	Other ident.	V	$B-V$	$U-B$
154660	HR 6361	6.357	0.211	0.103
−01° 3292B	ADS 10347B	9.71	0.66	0.15
	ADS 10347AB	6.308	0.227	0.094
154895	HR 6367	6.058	0.075	0.028
183324	V1431 Aql	5.801	0.086	0.067
187458	HR 7550	6.660	0.426	−0.056
162132	HR 6641	6.494	0.085	0.075
153808	ϵ Her	3.916	−0.024	−0.088
144206	υ Her	4.739	−0.096	−0.326

Notes. Magnitude and colours of ADS 10347AB are values resulting from co-added flux of HR 6361 and BD −01° 3292B measured simultaneously though a larger diaphragm in the photometer.

Table B.1. Journal of spectroscopic data of V2368 Oph.

Spg. no.	Time interval (HJD−2 400 000)	No. of spectra	Station, telescope and instrument
A	542 66.4–546 38.4	11	OND 2.0-m, grating spg.
B	543 39.7–551 02.6	19	DAO 1.22-m, grating spg.
C	527 45.8–527 49.0	21	SPM 2.1-m, echelle spg.
D	541 93.9–542 00.0	21	SPM 2.1-m, echelle spg.
E	542 50.8–542 53.0	12	SPM 2.1-m, echelle spg.