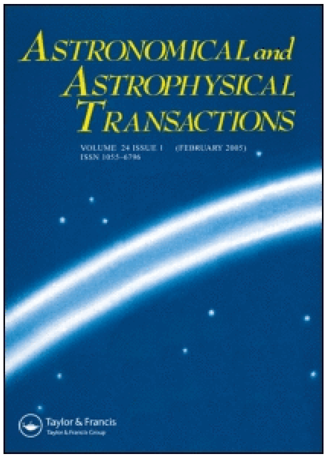

Astronomical & Astrophysical Transactions
The Journal of the Eurasian Astronomical Society
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453505

UBVR colours of accretion disks and power-law sources of radiation with interstellar reddening

N. G. Bochkarev [a]; E. A. Karitskaya [b]; N. I. Shakura [a]; S. A. Zhekov [ac]
[a] Sternberg Astronomical Institute, Moscow, USSR
[b] Astronomical Council of USSR Academy of Sciences, Moscow, USSR
[c] Bulgarian Academy of Science,

Online Publication Date: 01 January 1991
To cite this Article: Bochkarev, N. G., Karitskaya, E. A., Shakura, N. I. and Zhekov, S. A. (1991) 'UBVR colours of accretion disks and power-law sources of radiation with interstellar reddening', Astronomical & Astrophysical Transactions, 1:1, 41 - 50
To link to this article: DOI: 10.1080/10556799108244518
URL: http://dx.doi.org/10.1080/10556799108244518

Astronomical and Astrophysical Transactions, 1991,
Vol. 1, pp. 41–50
Reprints available directly from the publisher.
Photocopying permitted by license only

UBVR COLOURS OF ACCRETION DISKS AND POWER-LAW SOURCES OF RADIATION WITH INTERSTELLAR REDDENING

N. G. BOCHKAREV[1], E. A. KARITSKAYA[2], N. I. SHAKURA[1], and
S. A. ZHEKOV[1,3]

[1]*Sternberg Astronomical Institute, Moscow 119899, USSR*
[2]*Astronomical Council of USSR Academy of Sciences, Moscow, 109017, USSR*
[3]*On leave from Bulgarian Academy of Science.*

The (U–B), (B–V) and (V–R) colour indexes from accretion disks, and sources with power-law spectra, are calculated. They take into account interstellar extinction, in detail. Results are given on two-colour diagrams (U–B)–(B–V) and (B–V)–(V–R). Applications to Nova Vul 1988 and A0620–00 are discussed shortly.

KEY WORDS Accretion disks, colours—power-law-sources; colours—photometry of accretion disks, colours of X-ray binaries.

1. INTRODUCTION

The radiation of accretion disks is an important part of optical emission of X-ray binaries with low-mass optical components. Disk radiation predominates in the blue part of spectra, for such binaries as A0620-00, and Nova Vul 1988 (McClintock and Remillard, 1986; Borisov *et al.*, 1989), which are low-massive X-ray transients with faint optical components. In optical range, only photometric observations are usually available, and it is important to analyse UBVR colour-indexes, which can give us a chance to determine interstellar extinction A_v and disk characteristics (temperature, size and their time variations). Therefore, we have calculated the (U–B), (B–V), and (V–R) indexes for different parts, or models, of accretion disks, as well as for the sources with power-law and black-body spectra, taking into account interstellar extinction.

2. DISTRIBUTION OF TEMPERATURE ALONG DISK RADIUS

Temperature and emission spectrum of optically thick accretion disks are mainly formed as a result of either, dissipation of gravitational energy by friction of the gas layer (zone A of disk), or external illumination of the disk. For zone A, the distribution of temperature T along the disk radius R (Shakura and Sunyaev, 1973) is:

$$T/T_0 \propto R^{-3/4}, \tag{1}$$

where T_0 is the temperature of the disk outer edge. For low-massive systems, the external illumination is produced by an X-ray source located in the disk center. This source can have the indicatrix of radiation close to the spherical one, or can be a "flat" source mainly emitting normally to the disk plane.

In the case of external illumination, two asimptotic regimes can take place, and, according to them, there are zones B and C on the disk. For the disks illuminated by a central source, $T(R)$ depends on curvature of the disk surface, namely on disk thickness, as a function of R. In zone B, the disk thickness corresponds to the case of extracting gravitational energy (because of its domination), and $H \propto R^{9/8}$, but surface temperature is determined by outer illumination. For zone B and spherical indicatrix of the central source we have:

$$T/T_0 \propto R^{-15/64}. \tag{2}$$

For zone B and "flat" central source

$$T/T_0 \propto R^{-7/16} \tag{3}$$

In the zone C, the external heating dominates are so strong that the temperature of surface, of deep disk layers, and disk thickness, are determined by it; $H \propto R^{3/2}$. For zone C, and the spherical indicatrix of a central source, we have:

$$T/T_0 \propto R^{-3/7}. \tag{4}$$

For zone C and "flat" central source:

$$T/T_0 \propto R^{-1/3}. \tag{5}$$

3. CALCULATIONS OF SPECTRA AND COLOURS

The spectrum of radiation of each point of disk is assumed to be described by Planck function $B_\nu(T)$. The spectrum of a disk as a whole is determined only by distribution of temperature $T(R)$ (see (1)–(5)). Intensity of disk emission is equal to

$$I_\nu = 2\pi \int_0^{R_0} B_\nu(T(R))R \cos i \, dR, \tag{6}$$

where R_0 is the radius of the disk, and i is inclination of the disk surface to the line of sight. The optical radiation is mainly determined by the radiation of the outer zone of the disk. $T(R)$ we must assume, is determined by the mass ratio and geometry of the binary system. In the range $h\nu \ll kT$ spectra of disk radiation, all cases (1)–(5) are described by Rayleigh–Jeans law ($I_\nu \propto \nu^2$) and in the range $h\nu \gg kT$ by power-law function. For the cases (1), (4) and (5) $I_\nu \propto \nu^{1/3}$, $\nu^{-5/3}$, ν^{-3} respectively.

Spectra, calculated according to (6) with $T(R)$ from (1–5), as well as power-law spectra $I_\nu \propto \nu^{-\alpha}$ and black-body spectra $I_\nu = B_\nu(T)$, were integrated with transmission curves $f_i(\lambda)$ for photometric bands U, B, V, R (Beskin *et al.*, 1985; Straizys, 1977; Sapar and Malyuto, 1974; Buser, Kurucz, 1978) and with the curve of interstellar extinction A_λ (Whitford, 1958, Kaler, 1976). The later data of average extinction curves in the optical range (Sudzius, 1974) have extremely small differences with Whitford, 1958, Kaler, 1976. These differences cannot significantly influence the results of our calculations. In case (U–B), we take into account atmospheric extinction $p(\lambda)$, because of the U band feature in Johnson system (Straizys, 1977). Zero points of the colours were used from Beskin *et al.*, 1985; Straizys, 1977; Sapar and Malyuto, 1974; Buser and Kurucz, 1978.

4. RESULTS

Figure 1 shows two-colour diagrams (U–B)–(B–V) and (B–V)–(V–R) for accretion disks, according to (1)–(5) cases with different $\beta = d \ln T/d \ln R$ without interstellar extinction. Case (3) ($\beta = 7/16$) is distinguished from (4) ($\beta = 3/7$) not more than on a few hundredths in magnitude. For comparison, we give lines for power-law sources and black bodies.

Figure 2 shows the position of the power-law sources with interstellar reddening on the two-colour diagrams, and Figure 3 illustrates the same for accretion disks strongly illuminated by central sources (cases (4) and (5)). It is seen that, as in the well-known cases of stellar radiation (e.g. Straizys, 1977), slopes of reddening lines on the two-colours diagram (U–B)–(B–V) are increasing with reddening. The approximation of the reddening line with the constant slope E(U–B)/E(B–V) = 0.75 (Savage, Mathis, 1979) corresponding to the small interstellar extinction, is often used. However, it can produce great errors in estimations of accretion disks parameters.

Figure 4 shows dependences E(U–B)/E(B–V) on (B–V) for power-law spectra $I_\nu \propto \nu^{-\alpha}$ with different slopes α, and for A_υ from 0 to 7.5^m. Similar values for accretion disks with different $\beta = d \ln T/d \ln R$ lie on Figure 4, between Rayleigh-Jeans spectrum $\alpha = -2(T > 50{,}000\,\mathrm{K}$ for any β), and lines corresponding to high-frequency asymptotes of the disk spectra (e.g. $\alpha = 5/3$ for $\beta = 3/7$). It can be seen that E(U–B)/E(B–V) varys in wide limits from 0.72 to >1, and has a sufficiently strong dependence on object colour and its spectrum shape. Data on Figure 4 can be used for reduction of UBV observations for interstellar reddening.

UBVR colours of power-law spectra with different slopes α and accretion disks with different $\beta = d \ln T/d \ln R$ and outer rim temperature T_o are given in Tables 1, 2 as a function of interstellar extinction A_V.

5. APPLICATIONS TO NOVA VUL 1988 AND A0620-00

The crosses in Figure 2 and Figure 3 show data of individual photometric measurement on 1988 July 19 of Nova Vul 1988 (Borisov *et al.*, 1989). There, ovals of allowed values of 3σ significance level are also shown for it. During the outburst in 1988, this close binary with a low-mass optical component, had a bright evoluting accretion disk. From Figure 2 and Figure 3 we find the colours of the system can be approximated, either by emission of a power-law spectrum increasing with growth of frequency $\alpha \leqslant -2$ for interstellar extinction $A_V \leqslant 5.6^m$, or by radiation of an accretion disk with $25{,}000\,\mathrm{K} < T_o < 50\,000\,\mathrm{K}$ for $3 < A_V < 5.4^m$.

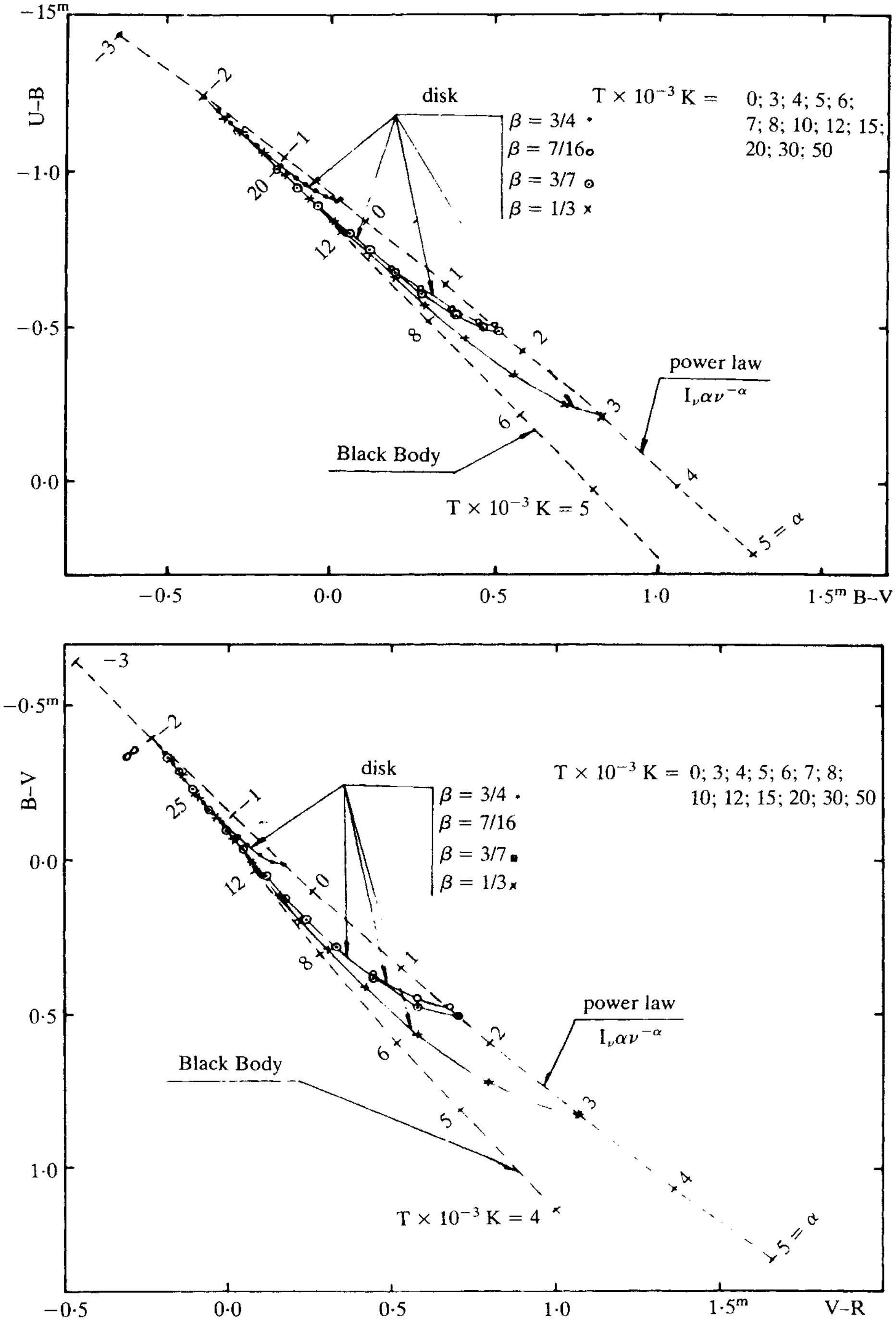

Figure 1 Two-colour diagrams (U–B)–(B–V) and (B–V)–(VR), for accretion disks with different $\beta = d \ln T / d \ln R$, and different temperature T, of outer disk edge (solid lines), for black bodies with temperature T and for sources of power-law spectra $I_\nu \propto \nu^\alpha$ with different α's without interstellar reddening.

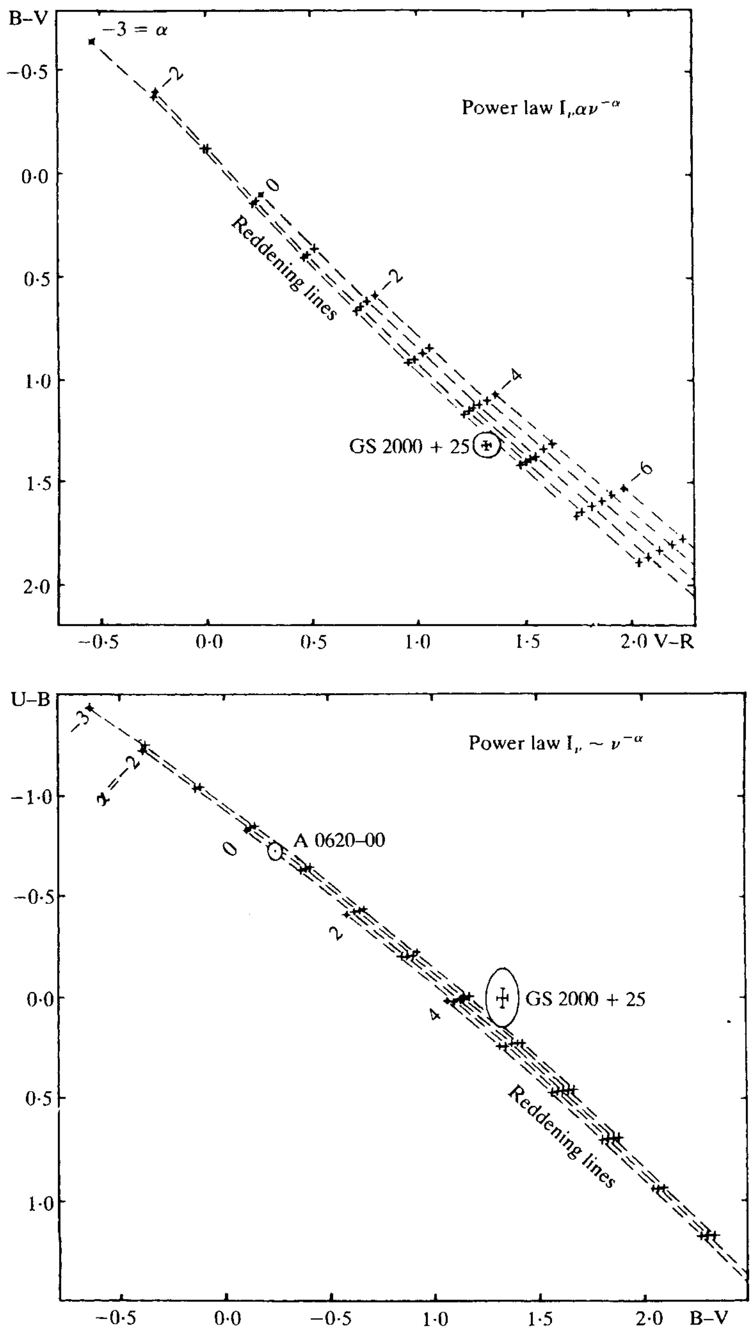

Figure 2 Interstellar reddening lines on the two-colour diagrams for sources with power-law spectra. Marks show the source positions for interstellar extinction with steps $\Delta A(H\beta = 4861\,\text{Å}) = 1$ stellar magnitude. Oval correspond to the dispersion of A0620-00 photometric observations near outburst 1975 maximum (Kurochkin *et al.*, 1988), and ovals of allowed position, with significantly level 3σ for a photometric measurement, 1988 July 19 of Nova Vul 1988 are shown.

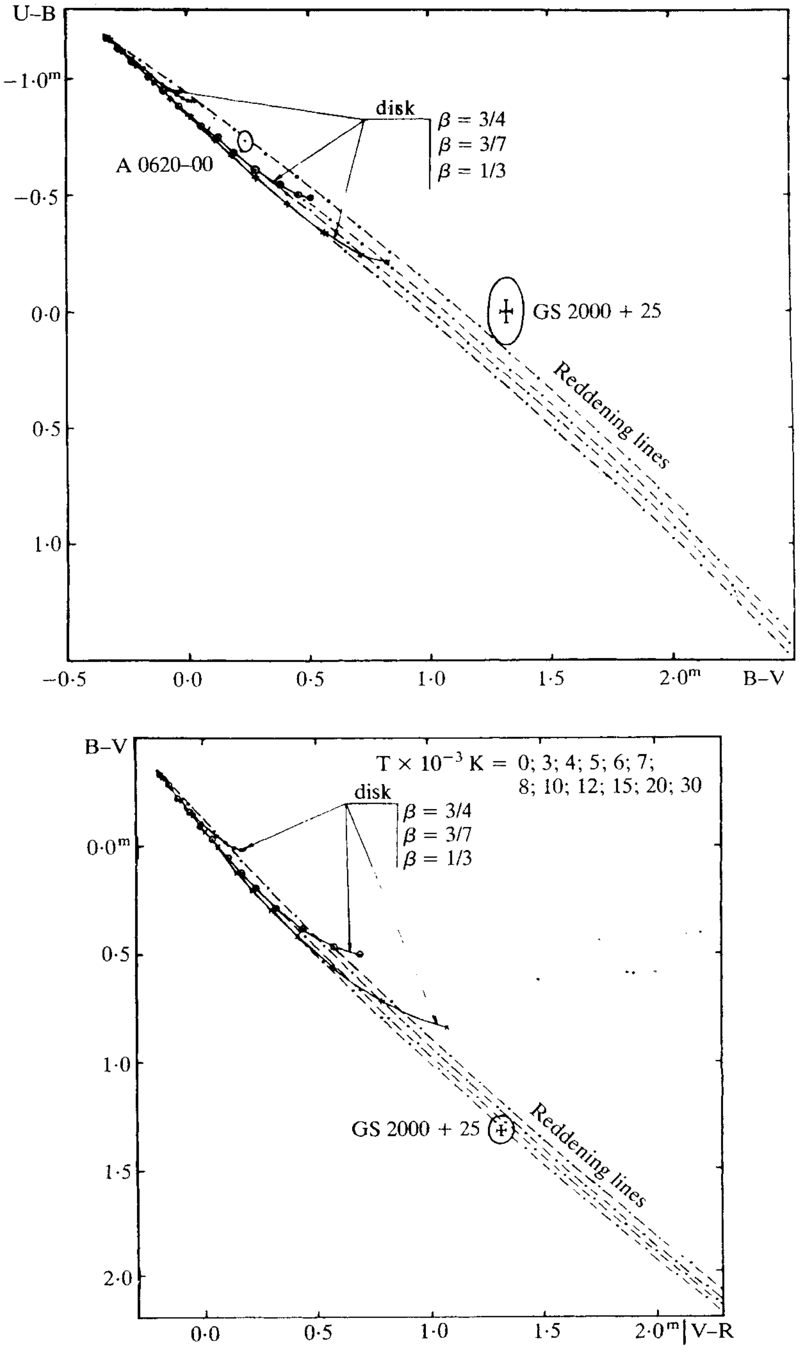

Figure 3 The same as on Figure 2 for accretion disks with $\beta = 3/7$ (case (4)), $T_o/1000\,\mathrm{K} = 3$, 5, 50 and with $\beta = 1/3$ (case (5)), $T = 50{,}000\,\mathrm{K}$. Marks are drawn with steps $\Delta A(H\beta) = 0.5$ mag.

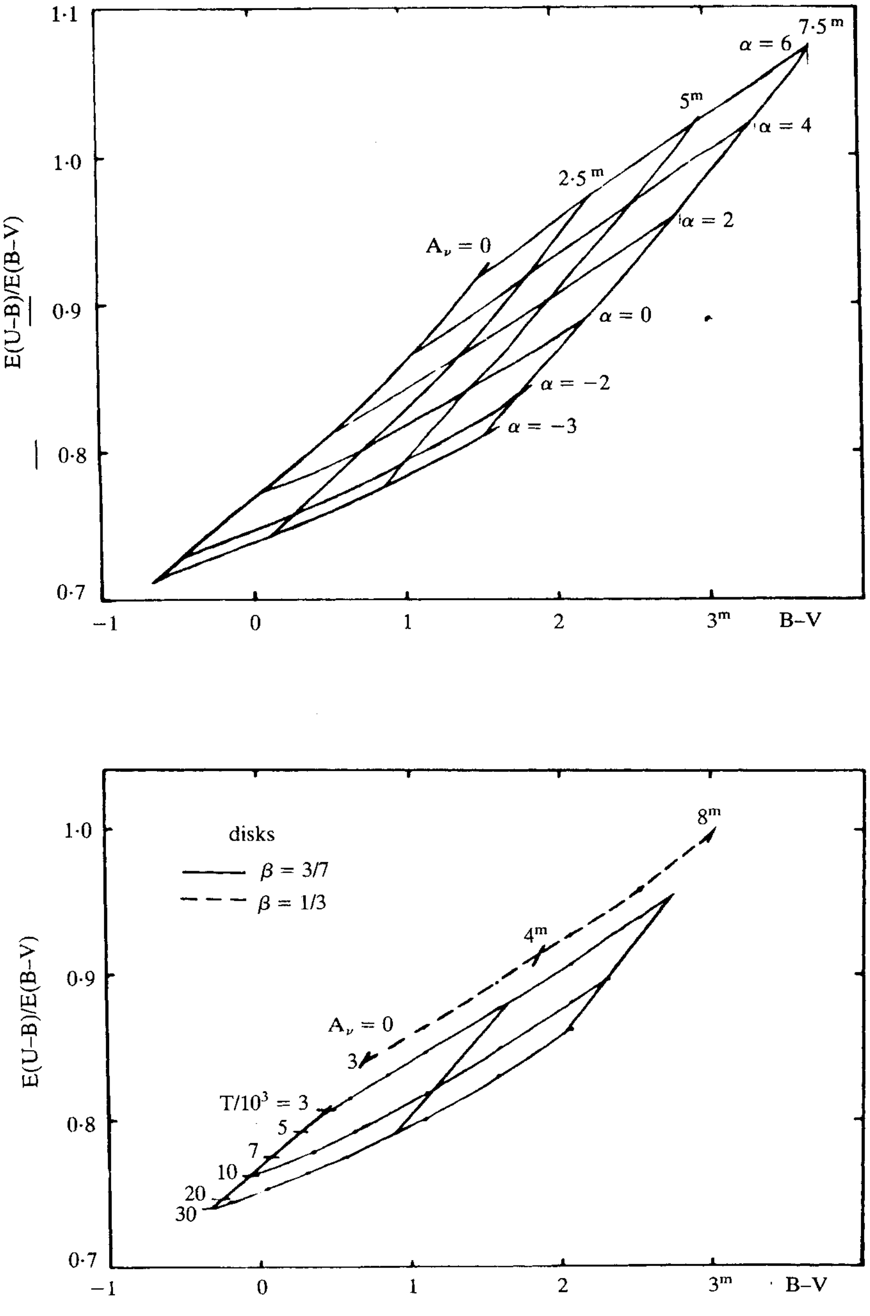

Figure 4 Dependence of slopes of the reddening E(U−B)/E(B−V) colours (a), for sources of power-law spectra $I_\nu \propto \nu^{-\alpha}$ with different α and (b) for accretion disks with $\beta = 3/7$ (solid lines) and $\beta = 1/3$ (dashed line). Temperatures T_0 of the outer disk ring are shown. Lines of equal values of interstellar extinction A_V are drawn on the both parts.

Table 1 UBVR colours of power-law spectra $I_\nu \propto \nu^\alpha$ as a function of interstellar absorption A_V for different α; E_{UB}/E_{BV} = E(U–B)/E(B–V); values A_V correspond with equal steps in $A(\lambda[H\beta] = 4681$ Å).

α	A_V	U–B	B–V	V–R	E_{UB}/E_{BV}	α	A_V	U–B	B–V	V–R	E_{UB}/E_{BV}
−3	0.000	−1.437	−0.643	−0.467	0.714	2	0.000	−0.418	0.588	0.799	0.818
	2.628	−0.848	+0.149	+0.228	0.743		2.560	+0.233	1.343	1.590	0.863
	5.216	−0.220	0.918	0.967	0.779		5.071	0.932	2.072	2.408	0.910
	7.753	+0.454	1.661	1.742	0.821		7.529	1.683	2.777	3.241	0.960
−2	0.000	−1.239	−0.392	−0.231	0.732	3	0.000	−0.204	0.827	1.078	0.839
	2.616	−0.640	+0.393	+0.484	0.764		2.544	+0.461	1.574	1.885	0.890
	5.189	+0.001	1.154	1.242	0.802		5.038	1.176	2.296	2.714	0.939
	7.715	0.690	1.888	2.031	0.846		7.479	1.941	2.996	3.554	0.989
−1	0.000	−1.039	−0.143	+0.014	0.751	4	0.000	+0.014	1.063	1.365	0.867
	2.602	−0.427	+0.634	0.749	0.787		2.528	0.692	1.803	2.186	0.916
	5.161	+0.227	1.387	1.523	0.827		5.005	1.424	2.519	3.025	0.968
	7.671	0.931	2.113	2.326	0.873		7.427	2.199	3.214	3.871	1.016
0	0.000	−0.835	+0.103	0.267	0.772	5	0.000	+0.237	1.298	1.659	0.895
	2.589	−0.211	0.873	1.022	0.811		2.512	0.929	2.030	2.493	0.945
	5.132	+0.457	1.618	1.812	0.853		4.971	1.672	2.740	3.341	0.996
	7.625	1.176	2.336	2.626	0.900		7.373	2.465	3.432	4.191	1.044
1	0.000	−0.628	0.347	0.529	0.794	6	0.000	0.463	1.529	1.961	0.913
	2.575	+0.009	1.109	1.302	0.836		2.495	1.170	2.256	2.806	0.974
	5.102	0.691	1.846	2.107	0.880		4.935	1.929	2.960	3.661	1.024
	7.578	1.425	2.558	2.931	0.929		7.318	2.735	3.651	4.513	1.071

Table 2 UBVR colours of accretion disks with different $\beta = d \ln T / d \ln R$ and different outer rim temperatures T_o as a function of interstellar extinction A_V; $E_{UB}/E_{BV} = E(U{-}B)/E(B{-}V)$; values A_V correspond equal steps of $A(\lambda[H\beta] = 4861$ Å); $T_3 = T_o/10^3$ K

					$\beta = 1/3$						
T_3	A_V	U–B	B–V	V–R	E_{UB}/E_{BV}	T_3	A_V	U–B	B–V	V–R	E_{UB}/E_{BV}
3	0.000	−0.244	+0.718	0.789	0.837	20	0.000	−1.057	−0.209	−0.096	0.747
	1.284	+0.078	1.093	1.172	0.861		1.309	−0.757	+0.183	+0.260	0.764
	2.556	0.414	1.461	1.564	0.887		2.607	−0.449	0.568	0.628	0.782
	3.816	0.761	1.822	1.963	0.911		3.895	−0.131	0.947	1.005	0.801
	5.063	1.121	2.177	2.367	0.936		5.172	+0.200	1.320	1.392	0.822
	6.297	1.494	2.527	2.774	0.961		6.436	0.543	1.686	1.786	0.844
	7.518	1.880	2.871	3.184	0.987		7.688	0.898	2.045	2.185	0.868
5	0.000	−0.463	0.411	0.417	0.805	30	0.000	−1.124	−0.275	−0.144	0.741
	1.294	−0.149	0.789	0.789	0.831		1.310	−0.826	+0.118	+0.210	0.758
	2.577	+0.175	1.160	1.170	0.852		2.610	−0.519	0.505	0.576	0.776
	3.847	0.512	1.525	1.558	0.875		3.900	−0.202	0.886	0.953	0.794
	5.106	0.859	1.883	1.954	0.896		5.178	+0.127	1.260	1.338	0.815
	6.353	1.220	2.235	2.355	0.923		6.444	0.468	1.628	1.731	0.837
	7.586	1.594	2.581	2.760	0.948		7.698	0.822	1.988	2.130	0.860
10	0.000	−0.839	+0.008	+0.068	0.766	50	0.000	−1.173	−0.325	−0.181	0.738
	1.304	−0.535	0.394	0.429	0.785		1.311	−0.876	+0.069	+0.172	0.754
	2.598	−0.222	0.774	0.801	0.805		2.613	−0.570	0.458	0.537	0.771
	3.880	+0.101	1.148	1.182	0.824		3.903	−0.255	0.839	0.913	0.789
	5.151	0.437	1.515	1.571	0.847		5.184	+0.073	1.215	1.297	0.809
	6.409	0.786	1.876	1.968	0.870		6.450	0.413	1.584	1.690	0.831
	7.655	1.148	2.229	2.369	0.894		7.705	0.766	1.946	2.089	0.854

Table 2 Cont'd

					$\beta = 3/7$						
T_3	A_V	U–B	B–V	V–R	E_{UB}/E_{BV}	T_3	A_V	U–B	B–V	V–R	E_{UB}/E_{BV}
3	0.000	−0.500	+0.468	+0.581	0.808	20	0.000	−1.072	−0.223	−0.105	0.746
	1.290	−0.183	0.849	0.961	0.832		1.309	−0.773	+0.169	+0.250	0.763
	2.570	+0.144	1.223	1.349	0.853		2.608	−0.465	0.555	0.617	0.781
	3.836	0.483	1.591	1.745	0.876		3.896	−0.147	0.934	0.995	0.799
	5.091	0.833	1.952	2.148	0.899		5.173	+0.183	1.308	1.381	0.820
	6.333	1.198	2.307	2.554	0.923		6.438	0.526	1.674	1.775	0.843
	7.561	1.579	2.656	2.964	0.950		7.690	0.882	2.033	2.175	0.866
5	0.000	−0.609	+0.285	+0.329	0.792	30	0.000	−1.132	−0.283	−0.150	0.743
	1.297	−0.298	0.667	0.698	0.815		1.311	−0.834	+0.110	+0.204	0.758
	2.583	+0.023	1.041	1.078	0.836		2.611	−0.528	0.497	0.570	0.775
	3.856	0.355	1.410	1.465	0.857		3.900	−0.211	0.878	0.946	0.793
	5.119	0.700	1.772	1.860	0.880		5.179	+0.118	1.253	1.331	0.814
	6.368	1.058	2.128	2.261	0.905		6.445	0.459	1.621	1.724	0.836
	7.605	1.429	2.477	2.666	0.930		7.699	0.812	1.981	2.124	0.859
10	0.000	−0.884	−0.032	+0.041	0.762	50	0.000	−1.178	−0.329	−0.184	0.737
	1.305	−0.581	+0.355	0.401	0.781		1.312	−0.881	+0.065	+0.169	0.754
	2.599	−0.269	0.737	0.772	0.800		2.613	−0.575	0.453	0.534	0.771
	3.883	+0.053	1.112	1.153	0.820		3.904	−0.259	0.835	0.909	0.789
	5.154	0.389	1.480	1.542	0.842		5.184	+0.068	1.211	1.294	0.809
	6.414	0.737	1.841	1.938	0.865		6.451	0.408	1.580	1.686	0.831
	7.661	1.098	2.196	2.339	0.889		7.706	0.761	1.942	2.085	0.853

					$\beta = 3/4$						
T_3	A_V	U–B	B–V	V–R	E_{UB}/E_{BV}	T_3	A_V	U–B	B–V	V–R	E_{UB}/E_{BV}
3	0.000	−0.904	+0.018	+0.166	0.762	20	0.000	−1.119	−0.268	−0.137	0.743
	1.302	−0.599	0.407	0.533	0.783		1.310	−0.821	+0.125	+0.217	0.759
	2.594	−0.284	0.790	0.912	0.803		2.610	−0.513	0.512	0.584	0.776
	3.874	+0.041	1.167	1.299	0.822		3.899	−0.197	0.893	0.960	0.795
	5.143	0.379	1.537	1.694	0.844		5.177	+0.133	1.267	1.346	0.815
	6.399	0.729	1.901	2.096	0.867		6.443	0.474	1.634	1.739	0.837
	7.642	1.093	2.258	2.502	0.891		7.697	0.828	1.995	2.139	0.860
5	0.000	−0.920	−0.020	+0.096	0.760	30	0.000	−1.160	−0.310	−0.170	0.739
	1.304	−0.616	+0.369	0.460	0.781		1.311	−0.862	+0.084	+0.184	0.755
	2.597	−0.302	0.752	0.834	0.800		2.612	−0.556	0.472	0.549	0.772
	3.879	+0.022	1.128	1.218	0.820		3.902	−0.240	0.853	0.925	0.790
	5.194	0.358	1.498	1.609	0.842		5.181	+0.088	1.229	1.310	0.811
	6.407	0.708	1.861	2.008	0.865		6.448	0.429	1.597	1.703	0.833
	7.653	1.070	2.218	2.411	0.889		7.703	0.782	1.959	2.102	0.856
10	0.000	−1.014	−0.152	−0.043	0.753	50	0.000	−1.192	−0.343	−0.195	0.736
	1.307	−0.713	+0.238	+0.315	0.770		1.312	−0.895	+0.051	+0.158	0.752
	2.604	−0.403	0.623	0.684	0.788		2.613	−0.591	0.440	0.523	0.768
	3.891	−0.084	1.001	1.063	0.807		3.905	−0.275	0.822	0.898	0.787
	5.165	+0.249	1.373	1.451	0.828		5.184	+0.053	1.198	1.282	0.807
	6.428	0.594	1.738	1.846	0.851		6.452	0.392	1.568	1.674	0.829
	7.263	0.831	1.977	2.113	0.866		7.708	0.744	1.930	2.073	0.852

Ovals corresponding to the dispersion of Nova Mon 1975/A0620-00 photometric observations near maximum of the 1975 outburst, are shown on Figure 2 and Figure 3 according to the data analysis of Kurochkin, Bochkarev, and Karitskaya (1988). The ovals can correspond to a disk heated model with spherical indicatrix for $T_o > 10{,}000$ K and $A_V > 0.87^m$. The most probable values are $T_o = 30{,}000$ K and $A_V \simeq 1.75^m$. The data can be described also by a power-law spectrum model with $\alpha = 0.5 \div -3$, $A_V = 0 \div 3^m$. Both models are in accordance with independent UV data, Wu *et al.* (1976), from which the $A_V \simeq 1.2 \div 1.3^m$, is followed. Earlier detailed analysis by Bocharev and Karitskaya (1979), was founded upon studying all available spectral ranges (including X-rays). This shows that, in principle, A_V can be between 0.5^m and 5^m.

References

Beskin, G. M., Lyutij, V. M., Neisvestnyj, S. I. *et al.* (1985). *Sov. Astron.* **29,** 252.

Bochkarev, N. G. and Karitskaya, E. A. (1979). *Astron. Tsirk,* No. 1035, 1.

Borisov, N. V., Bochkarev, N. G., Gladyshev, S. A. *et al.* (1989). Proc. 23rd ESLAB Symp., Bologna, Italy, 13–20 September, p. 305.

Buser, R. and Kurucz, R. L. (1978). *Astron. Astrophys.* **70,** 555.

Kaler, J. B. (1976). *Astrophys. J. Suppl. Ser.,* **31,** 517.

Kurochkin, N. E., Bochkarev, N. G. and Karitskaya, E. A. (1988). *Adv. Space Res.* 8, No. 2–3, 227.

McClintock, J. E. and Remillard, R. A. (1986). *Astrophys. J.,* **308,** 110.

Saper, A. and Malyuto, V. (1974). *Publ. Tartu Obs.,* **42,** 71.

Savage, B. D. and Mathis, J. D. (1979). *Ann. Rev. Astron. Astrophys.,* **17,** 73.

Shakura, N. I. and Sunyaev, R. A. (1973). *Astron. Astrophys.* **24,** 337.

Straizys, V. (1977). *Multicolour Stellar Photometry, Photometric Systems and Methods,* Moksalas Publ., Vilnius.

Sudzius, J. (1974). *Bull. Vilnius Obs.,* **39,** 18.

Whitford, A. E. (1958). *Astron. J.,* **63,** 201.

Wu, C.-C. *et al.* (1976). *Astron. Astrophys.,* **50,** 445.