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EMISSION-LINE STARS IN THE VILNIUS PHOTOMETRIC SYSTEM

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Abstract. Various types of emission-line stars, observed in the *Vilnius* photometric system, are analyzed. They include Be-type stars, Herbig Ae/Be stars, T Tauri-type stars and K- and M-type dwarfs with active chromospheres. It is shown that all stars of these types, except for late-type dwarfs, in their active stages can be identified by their interstellar reddening-free parameters. For emission-line stars of B and A types interstellar reddening determination is also possible.

Key words: stars: emission-line, photometric classification – Vilnius photometric system

1. INTRODUCTION

A considerable fraction of early-type stars show emission lines in their spectra. The domain of these stars extends from O5 to B9 spectral classes. The most numerous are Be-type stars which show the greatest concentration at B1–B3 classes of luminosities V–III, where about 20% of the stars exhibit hydrogen emission lines. O-type emission-line stars of Of and Oe types amount to 13% of all stars. Some hot emission stars belong to WR and P Cygni types, but these are not numerous. One more class of hot emission-line stars are young pre-main-sequence stars of B and A spectral classes, the so-called Herbig Ae/Be stars. They also exhibit hydrogen and sometimes other emission lines in their spectra. Among cooler emission-line stars the most numerous are young G–K–M dwarfs with active chromospheres, exhibiting emission cores of Ca II and sometimes hydrogen lines. A great variety of emissions is observed in pre-main-sequence T Tauri-type stars which cover the temperature range of G–K–M stars. These stars have also very peculiar spectral energy flux distribution curves. Among M-type stars the hydrogen emission lines appear also in the flare type dwarfs and the long-period variable giants near the maximum light. All these types of emission-line stars are described in more details in a monograph of one of the authors (Straižys 1992).

It is important to be able to identify faint emission-line objects in galactic fields where stars of various temperatures, luminosities, metallicities, peculiarities and interstellar reddenings are mixed together. For this purpose the photometric classification of stars is most important, since this method reaches fainter limiting magnitude than the spectroscopic method. The photometric identification of emission-line stars is especially important in CCD surveys of faint stars with ground-based and space telescopes.

Considerable efforts have been made for photometric identification of emission-type stars. Broad-band photometric systems in the visible and the near ultraviolet (like the *UBV* system) are not very informative in this respect since they are not sensitive enough to emissions appearing in spectral lines. Although some extreme Be, Ae/Be and T Tauri stars exhibit ultraviolet excesses, it is problematic to use this property for their photometric identification in the presence of interstellar reddening. More useful information can be obtained from infrared photometry since many of the emission-line stars of Be, Ae/Be and T Tauri types exhibit infrared excesses caused by the free-free emission of electrons in their gaseous envelopes or by thermal re-radiation of energy absorbed in their dust shells. However, the presence of infrared excess is a property not only of the mentioned types of stars but also of other types of stars with gaseous or dust envelopes.

Among medium-band photometric systems the system $uvby\beta$ was most frequently applied for the emission-line stars. The following types of emission-line stars have been investigated: Be-type stars by Crawford et al. (1975), Percy et al. (1981), Tobin (1985), Fabregat & Reglero (1990a) and Fabregat et al. (1996), T Tauri-type stars by Olson (1974), Mendoza et al. (1990), Gahm et al. (1993) and Terranegra et al. (1994), Ae/Be stars by Chkhikvadze (1990), Bibo & The (1991) and Terranegra et al. (1994), chromospheric

Ca II emission stars and active X-ray stars by Wilson & Skumanich (1964), Wilson (1966, 1968), Reglero et al. (1987), Fabregat & Reglero (1990b,c), Gimenez et al. (1991) and Morale et al. (1996). Observations of many Be and Ae/Be stars in the *uvby* system can be found in Manfroid et al. (1991, 1995) and Sterken et al. (1993, 1995).

Be-type stars cannot be identified in the *uvby* system without additional information from photometric or spectroscopic measurements of Hα or Hβ lines. The first of these lines gives more information since Be-type stars exhibit strong Balmer decrement, i.e., steep fall of emission intensity with increase of the line number. Herbig Ae/Be stars are easier to identify since the emission in their Hβ line is usually stronger than in ordinary Be stars and the Balmer jump is smaller than in normal stars of the same temperature. The photometric effect of F–G–K dwarfs with chromospheric emissions in H and K lines are too small to be detected photometrically in a medium-band system.

Many observations of Be and shell stars are also collected in the 13-color *Arizona* photometric system: Alvarez & Schuster (1981, 1982), Schuster & Alvarez (1983), Schuster & Guichard (1984). Ae/Be stars were also analyzed in the *Walraven* system (Tjin A Djie & The 1978, Tjin A Djie et al. 1984, The et al. 1985, 1986) and Be stars in the *Geneva* system (Golay et al. 1979, Hauck 1987). The emission-line star properties in the medium-band *Vilnius* system will be described below.

Narrow-band photometric systems, measuring intensities of Hα and other hydrogen lines, are the most effective in photometric identification of emission-line stars. Photoelectric measurements of Balmer lines of the emission-line stars were done and analyzed by Crawford et al. (1975), Abt & Golson (1966), Haug (1970), Peton et al. (1972), Feinstein (1974), Baliunas et al. (1975), Mendoza (1976, 1982, 1987), Baliunas & Guinan (1976), Feinstein & Marraco (1979), Claria & Escosteguy (1981), Ducati (1981, 1982), Herbst et al. (1982, 1983), Herbst & Layden (1987), Cester et al. (1982), Zeuge (1982), Mendoza et al. (1983).

For the interpretation of photometric effects in various passbands the most useful are atlases of spectra of emission-line stars published by Rydgren et al. (1976), Cohen & Kuhi (1979), Appenzeller et al. (1986), Valenti et al. (1993) and others.

The behavior of emission-line stars of various types in the *Vilnius* seven-color photometric system (Straižys 1992) has been analyzed in a number of papers. Straižys (1970, 1977, 1992) has demonstrated the identification of extreme Be-type stars in the interstellar reddening-free Q_{XZS},Q_{XYZ} diagram. Meištas (1982), Paupers et al. (1989) and Sūdžius (1994) showed the same for the Herbig Ae/Be stars and T Tauri-type stars in some two-color and Q, Q diagrams. The possibility of identification of emission-line stars is mainly based on photometric effect of emission of the Hα line in the S passband which has its mean wavelength at 656 nm and the half-width 20 nm. In some color indices, the photometric effect is caused by other strong emission lines and by the continuum emission in the ultraviolet.

2. OBSERVATIONS OF THE EMISSION-LINE STARS

(1) Observations of 29 B-type stars indicated in the literature by the suffix 'e' were selected from the General Photometric Catalogue of Stars Observed in the Vilnius System (Straižys & Kazlauskas 1993). From them, we used only 12 stars with the strongest emission in $H\alpha$ line, selected by the negative values of Q_{XZS}.

(2) Observations of three typical T Tauri-type stars (T Tau, RW Aur and WY Ari = LkHα 264) at different phases were taken from Paupers et al. (1989).

(3) 62 real and suspected Herbig Ae/Be stars at different phases were observed recently by Eimontas & Sūdžius (1998). We used the mean values of color indices of only 27 stars of this type with negative values of Q_{XZS} listed in Table 1.

(4) Twelve K- and M-type dwarfs with chromospheric emission lines, selected from the Third Catalogue of Nearby Stars (Gliese & Jahreiss 1991) and from the papers of Herbst & Layden (1987) and Robinson et al. (1990), were observed by K.Č. in 1989 and by S.B. in 1997 and 1998. Two of these stars (HD 221503 and BD−13 6464) were observed earlier, and their color indices from Straižys & Kazlauskas (1993) and from the new observations were averaged. Color indices of all these active red dwarfs are given in Table 2.

Table 1. Mean magnitudes and color indices of the Herbig Ae/Be stars observed by Eimontas & Sūdžius (1998). Only stars with strong emission in Hα are included.

Star	V	$U-V$	$P-V$	$X-V$	$Y-V$	$Z-V$	$V-S$
VX Cas	11.21	2.45	1.78	0.88	0.39	0.13	0.37
V594 Cas	10.60	1.96	1.56	1.16	0.58	0.20	0.92
HDE 283817	10.48	3.26	2.60	1.87	1.00	0.37	1.05
AB Aur	7.05	1.94	1.39	0.63	0.27	0.09	0.42
HK Ori	11.85	2.36	1.90	1.23	0.59	0.23	0.90
V380 Ori	10.53	1.93	1.63	1.18	0.57	0.16	1.00
MWC 120	7.91	1.71	1.17	0.52	0.24	0.08	0.34
MWC 789	9.53	1.49	1.08	0.51	0.24	0.08	0.47
MWC 137	12.16	2.31	2.04	1.96	1.07	0.35	2.50
MWC 147	8.73	1.32	1.08	0.79	0.44	0.16	0.76
R Mon	11.86	2.05	1.62	1.30	0.65	0.19	1.19
GU CMa	6.58	0.88	0.70	0.48	0.26	0.09	0.33
MWC 166	6.98	1.45	1.18	0.97	0.56	0.18	0.58
MWC 297	12.44	4.51	3.77	3.13	1.60	0.52	3.18
MWC 300	11.75	2.57	2.09	1.72	0.96	0.30	1.52
AS 310	11.90	3.31	2.46	1.67	0.84	0.27	1.04
MWC 314	9.92	3.62	2.95	2.46	1.39	0.49	1.75
V1295 Aql	7.86	1.96	1.32	0.58	0.25	0.09	0.37
V1685 Cyg	10.73	2.12	1.73	1.40	0.76	0.27	1.30
AS 442	10.93	2.92	2.11	1.31	0.65	0.23	0.73
LkHα 134	11.36	2.61	1.98	1.28	0.65	0.22	0.94
MWC 361	7.40	1.58	1.27	0.91	0.47	0.16	0.78
V361 Cep	10.26	1.75	1.37	0.93	0.49	0.17	0.62
V373 Cep	12.16	2.70	2.09	1.49	0.79	0.26	1.09
MWC 655	9.21	1.42	1.20	1.04	0.59	0.20	0.79
MWC 1072	10.21	2.12	1.52	0.94	0.48	0.18	0.55
IL Cep	9.28	2.18	1.77	1.35	0.74	0.25	0.77
BHJ 71	10.73	3.84	2.18	1.42	0.79	0.27	0.83
MWC 1080	11.57	3.33	2.69	2.21	1.18	0.40	1.67

Table 2. Magnitudes and color indices of K- and M-type dwarfs with chromospheric emission lines.

Gliese	HD, BD	Sp	V	$U{-}V$	$P{-}V$	$X{-}V$	$Y{-}V$	$Z{-}V$	$V{-}S$	n
488	111631	M1 Ve	8.50	4.51	3.85	2.78	1.01	0.63	1.13	4
508A	115953	M2 Ve	8.50	4.57	3.86	2.79	1.12	0.61	1.23	3
735		M2 Ve	10.05	4.64	3.82	2.77	1.20	0.58	1.32	3
782	191391	M0 Ve	8.92	4.25	3.71	2.60	0.90	0.60	1.03	3
815A		M3 Ve	10.12	4.45	3.74	2.81	1.16	0.65	1.29	2
825	202560	M0 Ve	6.69	4.44	3.83	2.74	1.05	0.63	1.15	2
867.1	214615	G9 Ve	7.73	2.84	2.40	1.65	0.63	0.27	0.63	3
868	214749	K5 Ve	7.83	3.89	3.44	2.36	0.81	0.52	0.87	4
873AB	+43 4305	M3 Ve	10.10	4.64	3.90	2.93	1.27	0.58	1.37:	2
879	216803	K5 Ve	6.47	3.78	3.32	2.30	0.79	0.50	0.82	3
898	221503	K5 Ve	8.62	4.24	3.73	2.61	0.88	0.58	1.05	2
907.1AB	−13 6464	K8 Ve	9.64	4.12	3.61	2.53	0.89	0.56	1.01	4

3. REDDENING-FREE Q,Q-DIAGRAMS

Various interstellar reddening-free Q-parameters of these stars were calculated by the equations

$$Q_{1234} = m_1 - m_2 - (E_{12}/E_{34})(m_3 - m_4). \qquad (1)$$

Here $m_1 - m_2$ and $m_3 - m_4$ are two color indices and E_{12} and E_{34} are their color excesses.

As it was shown in the above listed papers, the most effective parameter for identification of emission-line stars is Q_{XZS}. In Figs. 1, 2 and 3 we show the diagrams Q_{UPY} vs. Q_{XZS}, Q_{XYV} vs. Q_{XZS} and Q_{YZV} vs. Q_{XZS} with the emission-line stars plotted. It should be noticed that in these diagrams the emission-line stars of types Be, Ae/Be and T Tauri appear in the areas where no normal star of any luminosity is present.

The general property of the Be, Ae/Be and T Tauri stars in these diagrams is their strong displacement (up to 0.7 mag) in the direction of negative values of Q_{XZS} with respect to normal stars of similar temperatures and luminosities. Among the most displaced are Ae/Be stars V1685 Cyg, MWC 300, MWC 314, MWC 1080, VV Ser, R Mon, T Tauri-type star WY Ari and a peculiar Be supergiant P Cyg. Two

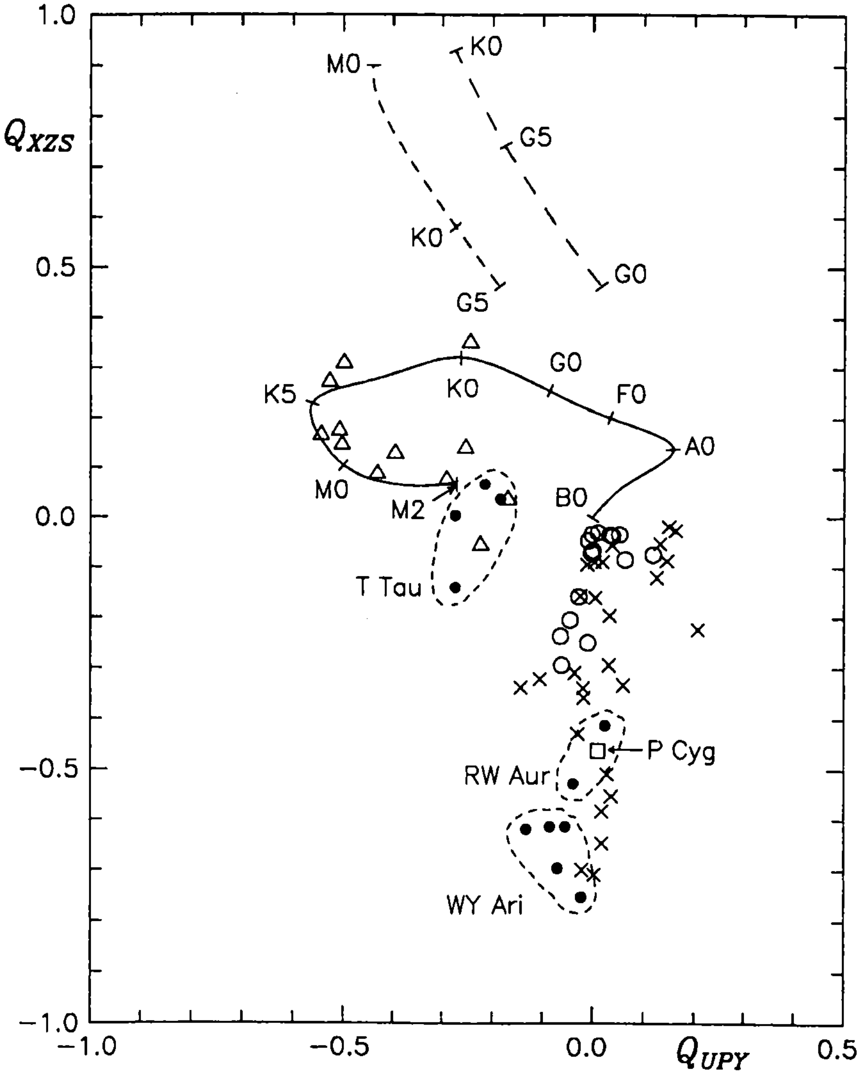

Fig. 1. Interstellar reddening-free diagram Q_{UPY},Q_{XZS}. The intrinsic lines of stars of normal chemical composition are shown: the solid line is for main-sequence stars, the short-dashed line is for giants and the long-dashed line is for supergiants. Open circles are for Be stars, $\times$ signs are for Herbig Ae/Be stars, dots are for T Tauri-type stars (circled by dashed curves) and triangles are for K–M dwarfs with active chromospheres.

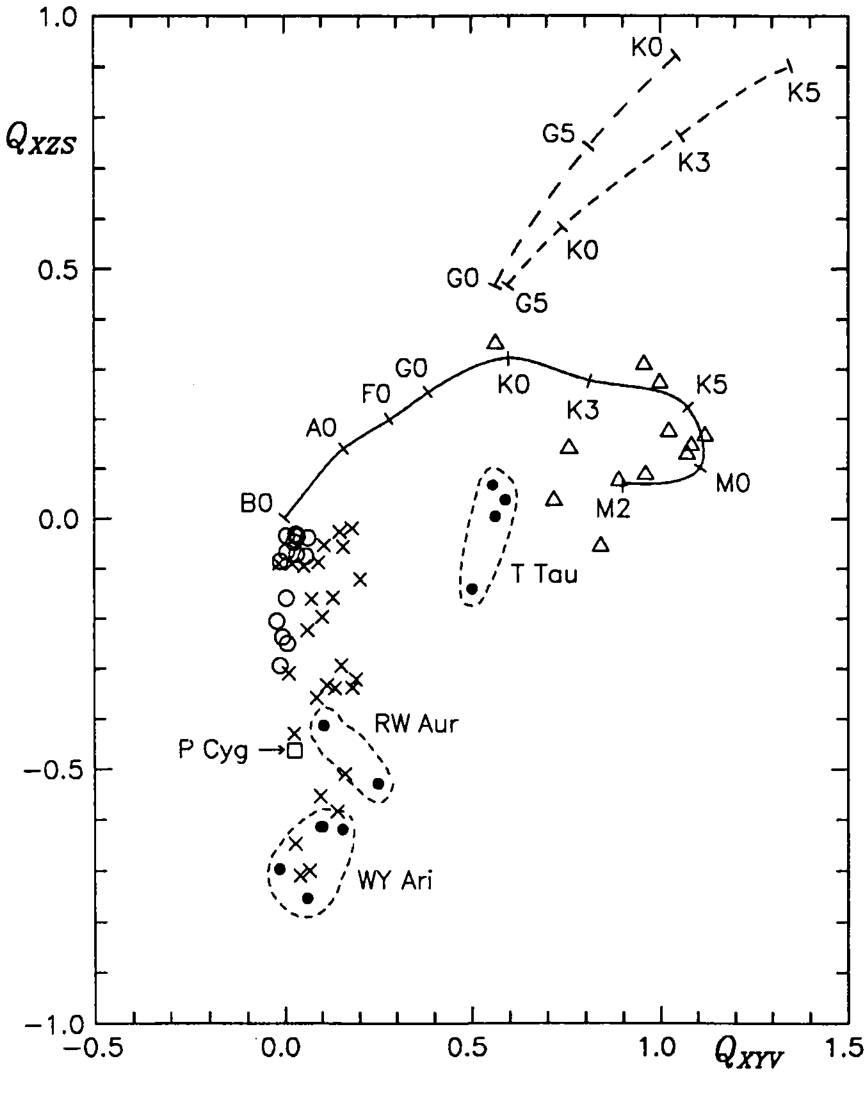

Fig. 2. Interstellar reddening-free diagram Q_{XYV},Q_{XZS}. Designations are the same as in Fig. 1.

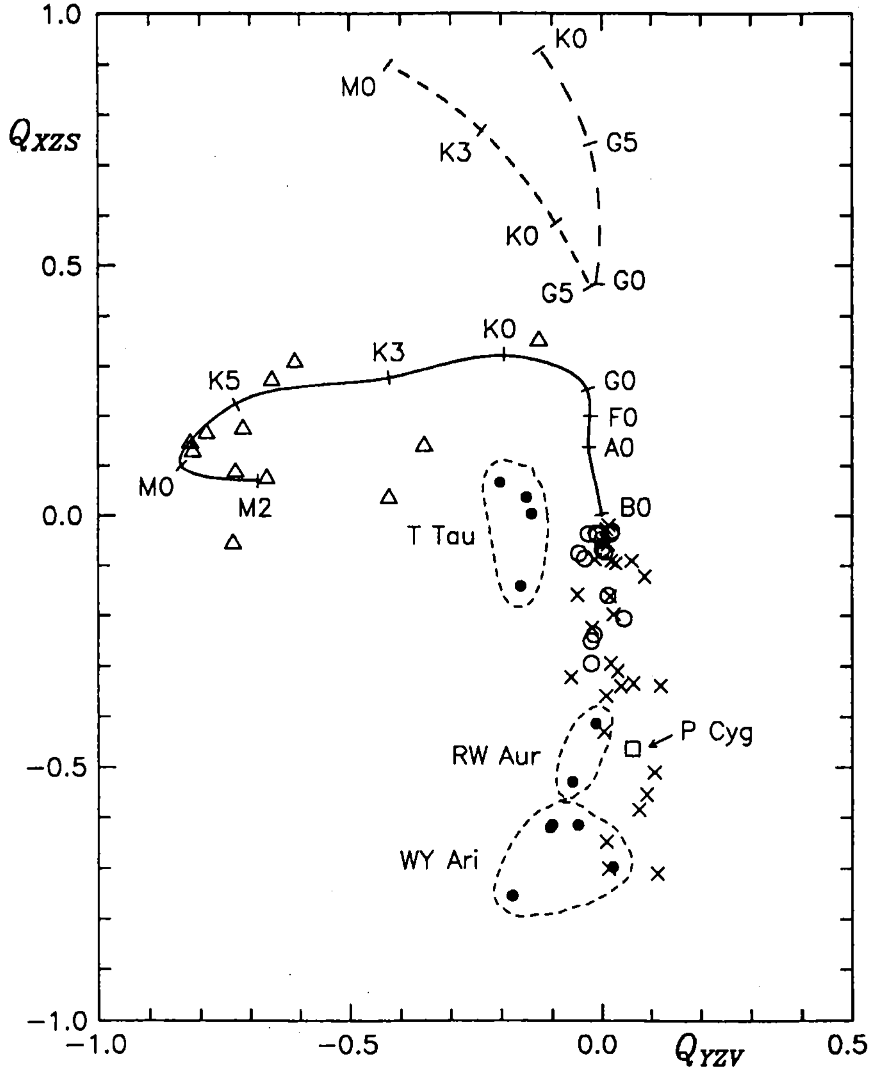

Fig. 3. Interstellar reddening-free diagram Q_{YZV},Q_{XZS}. Designations are the same as in Fig. 1.

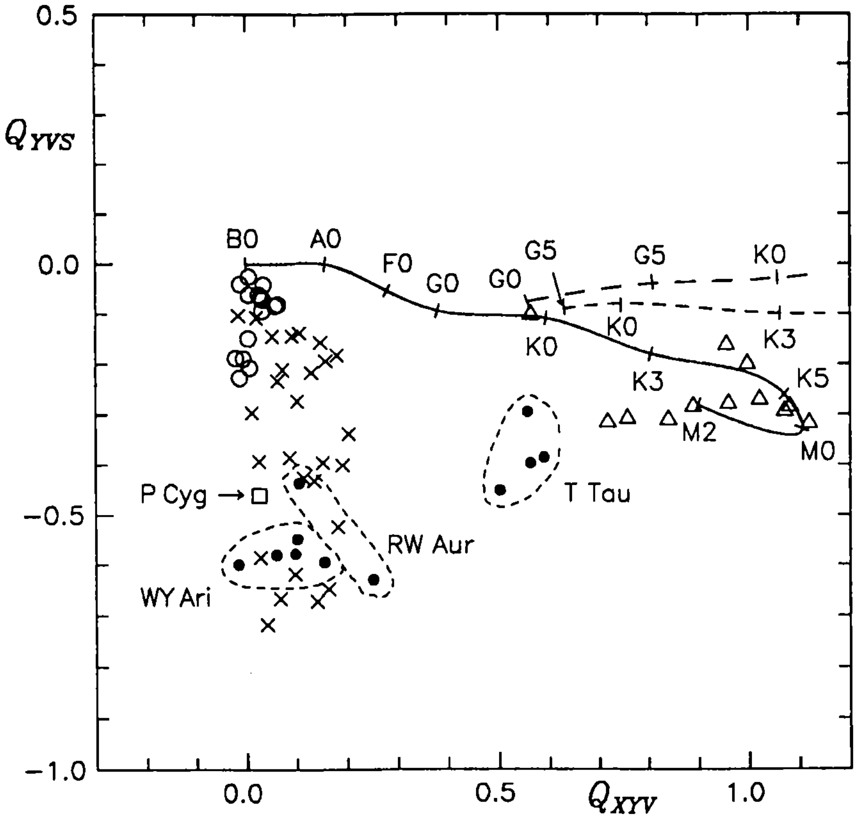

Fig. 4. Interstellar reddening-free diagram Q_{XYV},Q_{YVS}. Designations are the same as in Fig. 1.

Ae/Be stars, MWC 137 and MWC 297, exhibit extremely strong Hα emission: their $Q_{XZS} \approx -1.7$, i.e. these stars are outside the limits of our Q, Q diagrams. Extreme Be-type stars (ϕ Per, γ Cas, V2048 Oph, π Aqr) show about twice smaller displacements.

No doubt that the displacement is mainly caused by the Hα line emission on which the S passband of the *Vilnius* photometric system is centered. The rise of intensity in the S passband results in increase of the color index Z–S and reduction of the reddening-free parameter Q_{XZS}. An additional effect in the same direction is caused by the emission lines in the X passband at 405 nm.

Some Be and Ae/Be stars show only small, if any, displacement from the position of normal B and A type stars. These stars probably are either mild cases of emission-line stars or they have lost their emission lines by the time of the photometric observations. This is a well-known phenomenon in Be-type stars caused by density changes in circumstellar gaseous disk or envelope. A similar conclusion has been reached by Mendoza et al. (1983) from narrow-band Hα photometry of Be stars.

It is expected that the emission in Ca II H and K lines in G–K–M stars with active chromospheres must affect the flux measured in the X passband, since both lines are on the wing of the X response function (at 393.4 nm and 396.8 nm), where the sensitivity is about 2/3 of the maximum level. Due to this effect the color index X–Z and the parameter Q_{XZS} should be smaller. On the other hand, if the emission in Hα line is present, it should also diminish the same Q-parameter. However, the emissions in H+K lines and in Hα line usually are not correlated (Giampapa et al. 1989, Robinson et al. 1990).

The majority of K–M dwarfs of "emission" type, plotted in Figs. 1, 2 and 3 by triangles, show no systematic shift from the sequence of normal dwarfs. Only the star Gliese 815A shows the displacement of $\sim$ 0.1 mag in the expected direction. This means that the effect of chromospheric emission of these stars during the observations was too small to be detected photometrically with the *Vilnius* filters. It is possible that the observed emission-line dwarfs were in a low activity stage during our observations. Therefore, much longer observing runs for emission-line stars of this type are essential.

Other photometric effect, which is seen when comparing the three Q, Q diagrams for T Tauri-type stars, is not related with the Hα emission: with increasing emission intensity of Hα, the parameters Q_{UPY} and Q_{YZV} show the shifts to more positive values and the parameter Q_{XYV} shows a shift to more negative values than normal dwarfs of similar temperature. The spectral classes of the observed T Tauri stars according to Herbig & Bell (1988) are: K5 for WY Ari, K1: for RW Aur and K0 for T Tau. The shift from the corresponding main-sequence points for WY Ari, the extreme T Tauri star, is $\sim$ +0.5 mag in Q_{UPY}, $\sim$ −1.0 mag in Q_{XYV} and $\sim$ +0.6 mag in Q_{YZV}.

The increase in Q_{UPY} can be explained by making the color U–P more positive and (or) color P–Y more negative. This can happen when the effect is due to strong emission in the P passband caused by collective action of the high members of the Balmer series. The decrease in Q_{XYV} is probably related to strong emission in the X passband: the Balmer lines Hδ and Hϵ and the Ca II lines H and K. The increase in Q_{YZV} can be the result of emissions of Mg I triplet and some Fe II lines in the Z passband.

The diagram Q_{YZV},Q_{XZS} is also very useful for the classification of normal G5–M stars by luminosity classes.

One more very useful diagram, Q_{XYV},Q_{YVS}, is shown in Fig. 4. This diagram differs from Fig. 2 only by the Q-parameter, plotted on the y-axis. The parameter Q_{YVS} does not contain the passband X, and the only passband with strong emission is S. Thus, the parameter Q_{YVS} seems to be the best measure of the intrinsic intensity of the Hα line. This parameter is slightly smaller than Q_{XZS} because of the absence of the additional effect of emissions in the X passband.

The diagrams of Figs. 2 and 4 are also useful for photometric separation of classical Be stars and the Herbig Ae/Be stars: only some Herbig stars appear in the Be domain.

4. INTERSTELLAR REDDENING

The interstellar reddening of emission-line stars can be estimated from two-color diagrams with color indices which are not affected by strong emission lines. In the case of Be and Ae/Be stars such color indices are Y–Z and Z–V. The Z–V vs. Y–Z diagram for emission-line stars is plotted in Fig. 5. It is evident that Be and Ae/Be stars lie on it along the reddening line of normal O–B–A stars. If at least the one-dimensional spectral class of the emission-line star is available, we can determine its color excesses $E_{Y-Z} = (Y - Z)_{\rm obs} - (Y - Z)_0$ and $E_{Z-V} = (Z - V)_{\rm obs} - (Z - V)_0$. Here $(Y - Z)_0$ and $(Z - V)_0$ are the intrinsic color indices given in Table 3 for the corresponding spectral classes. Approximate spectral classes of Be and Ae/Be stars can be estimated from the Q, Q-diagrams shown in Figs. 1–4. The accuracy of the color-excess determination should be not worse than 0.03 mag.

5. CONCLUSIONS

The following conclusions can be made from the above analysis of photometric behavior of emission-line stars in the diagrams of the *Vilnius* system.

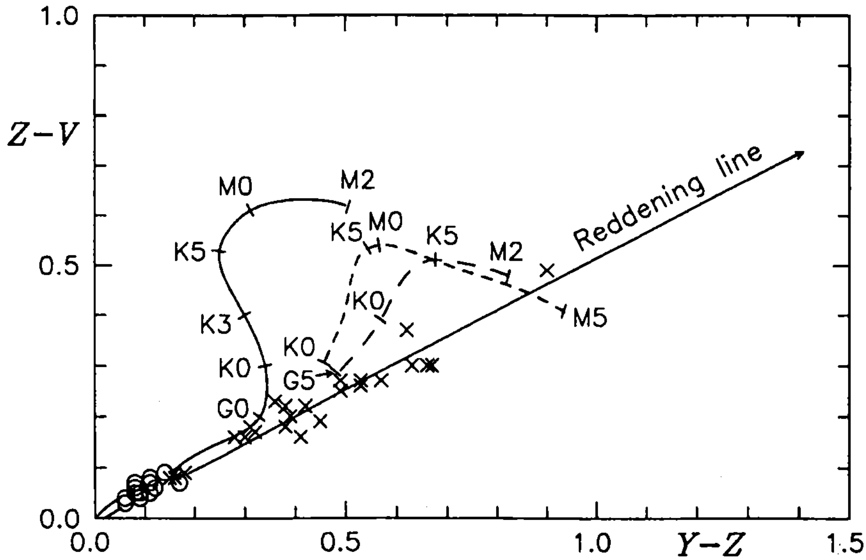

Fig. 5. Two-color diagram Z–V vs. Y–Z for determination of interstellar reddening of emission-line stars. Designations are the same as in Fig. 1.

Table 3. Intrinsic color indices of B and A stars of luminosity class V, necessary for the determination of color excesses of Be and Herbig Ae/Be stars (from Straižys 1992).

Sp	Y–Z	Z–V	Sp	Y–Z	Z–V
B0	0.00	0.00	B9	0.08	0.06
B1	0.01	0.01	A0	0.10	0.07
B2	0.02	0.02	A1	0.11	0.08
B3	0.04	0.03	A2	0.12	0.08
B5	0.06	0.04	A3	0.14	0.08
B6	0.06	0.04	A5	0.16	0.10
B7	0.06	0.04	A7	0.17	0.10
B8	0.07	0.05	F0	0.21	0.13

(1) Emission-line stars of Be, Herbig Ae/Be and T Tauri types can be identified in some interstellar reddening-free Q,Q diagrams of the *Vilnius* system. These stars occupy the diagram regions where other types of stars do not appear.

(2) Extreme Ae/Be stars and T Tauri-type stars in the investigated Q,Q diagrams occupy the same area and cannot be separated photometrically. However we expect that their separation is possible in multidimensional spaces using three, four or five independent Q-parameters.

(3) The photometric emission effects for all classical Be-type stars are much smaller than for Ae/Be-type stars and T Tauri-type stars.

(4) Emission-line stars of type Ae/Be with moderate emission strength in the Q_{UPY},Q_{XZS} and Q_{YZV},Q_{XZS} diagrams (Figs. 1 and 3) occupy the same area as the classical Be stars. However, their position is somewhat different in the Q_{XYV},Q_{XZS} and Q_{XYV},Q_{YVS} diagrams (Figs. 2 and 4) due to parameter Q_{XYV}. Consequently, their photometric separation is possible.

(5) For the majority of G–K–M dwarfs with chromospheric emission lines the photometric effect of the emission is too small to be detected by medium-band photometry.

(6) It is possible to estimate the interstellar reddening of Be and Ae/Be stars with an accuracy of 0.03 mag.

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