АСТРОНОМИЧЕСКОЕ ОБЩЕСТВО

EURO–ASIAN ASTRONOMICAL SOCIETY

Round **Theo**

Group **α**

XIV Международная астрономическая олимпиада

XIV International Astronomy Olympiad

Китай, Ханчжоу 8 – 16. XI. 2009 Hangzhou, China

язык / language **English**

Theoretical round. Problems to solve

General note. Maybe not all problems have correct questions. Some questions (maybe the main question of the problem, maybe one of the subquestions) may have no real sense. In this case you have to write in your answer (in English or Russian): «**impossible situation – ситуация невозможна**». Of course, this answer has to be explained numerically or logically.

Data from the table of planetary data may be used for solving every problem.

The answers «Да-Yes» or «Нет-No» has to be written in English or Russian.

1. **Sirius.** It is known that the so called "Dog Star" (Sirius) is the brightest star in the Chinese sky. And in what else districts on the Earth Sirius is also the brightest star in the real sky of this district? What are numerical characteristics of the borders of these districts? Note: you should take into account only stars in their historical-classical meaning, i.e. Sun, planets, etc. should not be taken into account.

2. **Number of molecules.** Estimate the number of molecules in the Earth's atmosphere.

3. **Efficiency of eye.** Estimate the theoretical limit of the maximum magnitude of stars that the human eye can see under very optimal conditions. Take into account that the eye's retina "remembers" the image about 1/7 of a second. A 0^m star sends us about 10^{10} photons/m^2 every second.

4. **Catastrophe.** Imagine, that on July 5, 2084 the mass of the Sun suddenly has decreased to half its original value. Calculate a new period of revolution of the Earth around of the new Sun.

5. **Mirror for a telescope.** You have a disc of glass with thickness b = 40 mm, from which one has to make (by grinding) a spherical mirror with a diameter of D = 500 mm. What could the focal distances F be of a mirror made from this disc?

Theoretical round. Problems to solve

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1. **Sirius.** It is known that the so called "Dog Star" (Sirius) is the brightest star in the Chinese sky. And in what else districts on the Earth Sirius is also the brightest star in the real sky of this district? What are numerical characteristics of the borders of these districts? Note: you should take into account only stars in their historical-classical meaning, i.e. Sun, planets, etc. should not be taken into account.

2. **Number of molecules.** Estimate the number of molecules in the Earth's atmosphere.

3. **Eris.** The largest discovered now in our Solar system Transneptune body is the dwarf planet Eris (Эрида). Now Eris is near its aphelion point. Find the apparent stellar magnitude of Eris as visible from Earth. Approximately when will the next "Great opposition" of Eris be? What will the magnitude of Eris be as visible from Earth at this "Great opposition"?

4. **Catastrophe.** Imagine, that on July 5, 2084 the mass of the Sun suddenly has decreased to half its original value. Calculate a new period of revolution of the Earth around of the new Sun.

5. **Galaxy pair.** This famous galaxy pair contains two interacting galaxies, IC563 and IC564. The coordinates of the centers of IC563 and IC564 are respectively RA 146.58479, DEC 3.04558 and RA 146.58783, DEC 3.07137. Using the 2.16m telescope of The National Astronomical Observatories of China (NAOC), their R-band image in 2009 has been obtained, which is presented at the fig.1. The spectrum of the center of IC563 is shown at the fig.2.

5.1. We were assigned two periods of time in 2009 to carry out our observation. One was in April and another was in September. Please find out, when IC563, IC564 has been observed? (Write "**Apr**" or "**Sep**" in English.)

5.2. Mark IC563 and IC564 at the fig.1.

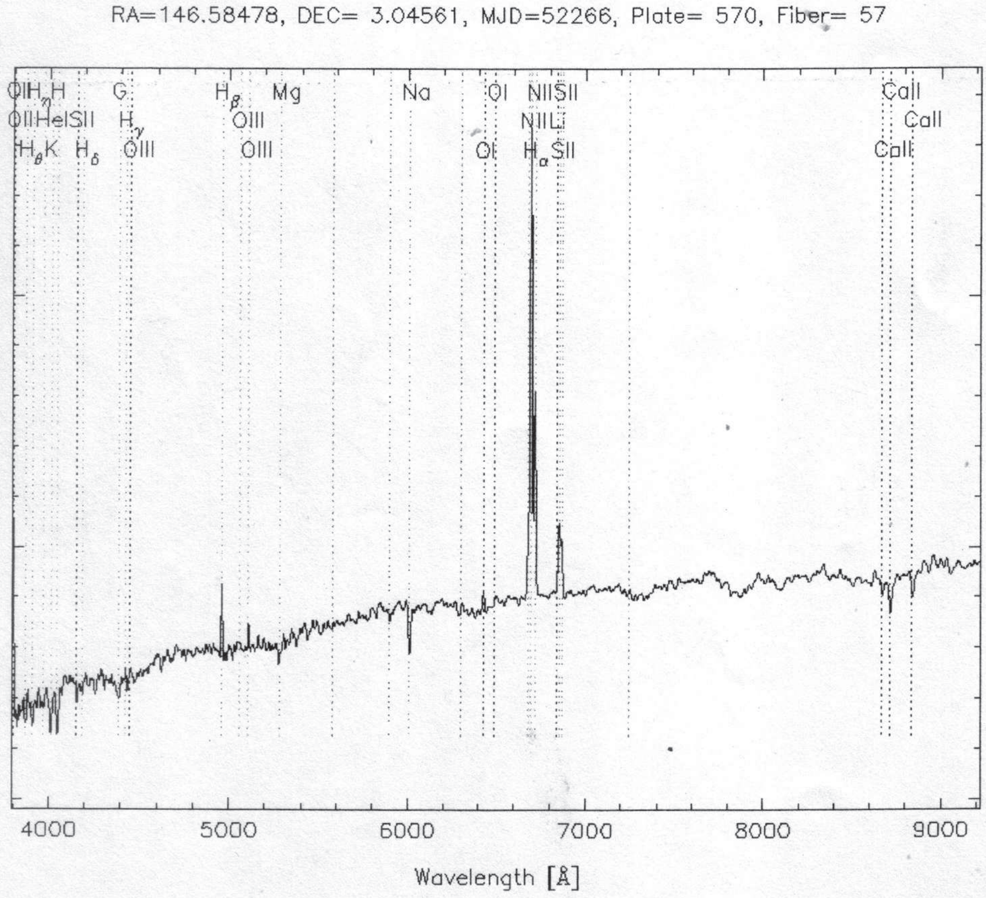
5.3. Find out the redshift of the galaxies. Consider the redshift of one of them can be realized as the redshift for the other.

5.4. NAOC astronomers want to take Hα photo of IC563 and IC564 next year to seek the star formation regions in or around them. There is a series narrow band Hα transmission filters in NAOC, as listed in table (the center wavelength is given in the terms of velocity). Select the most suitable filter for the observation.

5.5. How many parsecs away are the galaxies? What is the projected distance between the two galaxies?

Задача 5. Рисунки. Таблица

Problem 5. Figures. Table



№	(%)	Hα
№ фильтра	максимум пропускания (%)	пик по красному смещению для Hα (км/с)
№ of filter	maximum transmission (%)	peak value of redshift for Hα (km/s)
C1	80	0
C2	78	2150
C3	89	3600
C4	78	6720
C5	82	9006
C6	81	11290
C7	87	13570
C8	78	15400
C9	84	18600
C10	84	20890

Элементы орбит.
Физические характеристики некоторых планет, Луны, Солнца и Эриды

Parameters of orbits.
Physical characteristics of some planets, Moon, Sun and Eris

Небесное тело, планета	Среднее расстояние от центрального тела		Сидерический (или аналогичный) период обращения		Эксцентриситет,	Экваториальн. диаметр	Масса	Средняя плотность	Ускор. своб. пад. у пов.	Макс. блеск, вид. с Земли **)	Альбедо
	в *астр. ед.*	в *млн. км*	в тропич. годах	в средних сутках	*e*	*км*	10^{24} *кг*	*г/см*^{3}	*м/с*^{2}		
Body, planet	Average distance to central body		Sidereal (or analogous) period		Eccentricity	Equat. diameter	Mass	Av. density	Grav. acceler. at surf.	Max. magn. from Earth **)	Albedo
	in *astr. units*	in *mln. km*	in troph. years	in days	*e*	*km*	10^{24} *kg*	*g/cm*^{3}	*m/s*^{2}		
Солнце Sun	$1,6\cdot10^9$	$2,5\cdot10^{11}$	$2,2\cdot10^8$	$8\cdot10^{10}$		1392000	1989000	1,409		$-26,8^m$	
Меркурий Mercury	0,387	57,9	0,241	87,97	0,206	4 879	0,3302	5,43	3,70		0,06
Венера Venus	0,723	108,2	0,615	224,70	0,007	12 104	4,8690	5,24	8,87		0,78
Земля Earth	1,000	149,6	1,000	365,26	0,017	12 756	5,9742	5,515	9,81		0,36
Луна Moon	0,00257	0,38440	0,0748	27,3217	0,055	3 475	0,0735	3,34	1,62	$-12,7^m$	0,07
Марс Mars	1,524	227,9	1,880	686,98	0,093	6 794	0,6419	3,94	3,71	$-2,0^m$	0,15
Юпитер Jupiter	5,204	778,6	11,862	4 332,59	0,048	142 984	1899,8	1,33	24,86	$-2,7^m$	0,66
Сатурн Saturn	9,584	1433,7	29,458	10 759,20	0,054	120 536	568,50	0,70	10,41	$0,7^m$	0,68
Эрида Eris	68,01			204 862	0,434	2 600	0,0167		0,8		0,86

**) Для Луны – в среднем противостоянии.
**) For Moon – in mean opposition.

Некоторые константы и формулы

Some constants and formulae

Скорость света в вакууме, c (м/с)	299 792 458	Speed of light in vacuum, c (m/s)
Гравитационная постоянная, G ($Н·м^2/кг^2$)	$6.674 \cdot 10^{-11}$	Constant of gravitation, G ($N·m^2/kg^2$)
Солнечная постоянная, A ($Вт/м^2$)	1367	Solar constant, A (W/m^2)
Постоянная Хаббла, H_0 (км/с/МПк) — среднее значение	70	mean value — Hubble constant, H_0 (km/s/Mpc)
Постоянная Хаббла, H_0 (км/с/МПк) — диапазон значений	50-100	diapason of values — Hubble constant, H_0 (km/s/Mpc)
Постоянная Планка, h (Дж·с)	$6.626 \cdot 10^{-34}$	Plank constant, h (J·s)
Заряд электрона, e (Кл)	$1.602 \cdot 10^{-19}$	Charge of electron, e (C)
Масса электрона, m_e (кг)	$9.109 \cdot 10^{-31}$	Mass of electron, m_e (kg)
Соотношение масс протона и электрона	1836.15	Proton-to-electron ratio
Постоянная Фарадея, F (Кл/моль)	96 485	Faraday constant, F (C/mol)
Магнитная постоянная, μ_0 (Гн/м)	$1.257 \cdot 10^{-6}$	Magnetic constant, μ_0 (H/m)
Универсальная газовая постоянная, R (Дж/моль/K)	8.314	Universal gas constant, R (J/mol/K)
Постоянная Больцмана, k (Дж/K)	$1.381 \cdot 10^{-23}$	Boltzmann constant, k (J/K)
Стандартная атмосфера (Па)	101325	Standard atmosphere (Pa)
Постоянная Стефана-Больцмана, σ ($Вт/м^2/K^4$)	$5.670 \cdot 10^{-8}$	Stefan-Boltzmann constant, σ ($W/m^2/K^4$)
Константа смещения Вина, b (м·K)	0.002897	Wien's displacement constant, b (m·K)
Лабораторная длина волны Hα (Å)	6563	Laboratory wavelength of Hα (Å)
Показатель преломления воды при 20°C, n	1.334	Refractive index of water for 20°C, n
Площадь сферы	$S = 4\pi R^2$	Area of sphere
π	3.14159265	π

Данные о некоторых звёздах

Data of some stars

			RA	DEC	m	SC
Арктур	Arcturus	α Boo	$14^h 15^m 40^s$	19° 10' 57"	-0.05	K1
Вега	Vega	α Lyr	$18^h 36^m 56^s$	38° 47' 01"	0.03	A0
Денеб	Deneb	α Cyg	$20^h 41^m 26^s$	45° 16' 49"	1.25	A2
Полярная	Polaris	α UMi	$02^h 31^m 51^s$	89° 15' 51"	2.02	F7
Сириус	Sirius	α CMa	$06^h 45^m 09^s$	-16° 42' 58"	-1.46	A1

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Theoretical round. Sketches for solutions

Note for jury and team leaders. The proposed sketches are not full; the team leaders have to give more detailed explanations for students. But the correct solutions in the students' papers (enough for 8 pts) may be shorter.

αβ-1. Sirius. Sirius is the brightest star (in historical-classical meaning of a star) on the Earth's sky. Therefore in a first approximation it will be the brightest star in those districts on the Earth where it is visible, that is, at least sometimes appears over horizon. As the declination of Sirius is $\delta = -16°43'$, it will be visible in all southern hemisphere, and also in northern hemisphere at latitudes not nearer 16°43' to the pole, that is, at latitudes not higher 73°17' North. Theoretically, in the second approximation refraction may be taken into account (35' at horizon). With the refraction Sirius can be above horizon at districts till latitudes of 73°52' North. But refraction doesn't matter for our goal. There is a talk about real (not theoretical) sky in the text. In the third approximation light absorption should be taken into account. It is obvious that Vega or Arcturus in high sky essentially are more bright than Sirius at horizon. Heights on which Sirius becomes weaker than Vega or Arcturus may be roughly estimated as ~5÷8°. Thus, Sirius is the brightest star in the sky for districts to the south from the latitudes of 65°÷ 69° North.

Note for jury: the solution without a correct mention of refraction (that is, without mentions that it not effected here) should be estimated with a deduction of 0.5 points. Values ~5÷8° are approximate, it is important the understanding of the effect and a correct order of this height.

αβ-2. Number of molecules. The pressure of an atmosphere is the total weight of all number (N) of its molecules, distributed over the whole surface of a planet, that is,

$$P = N \cdot m \cdot g / S,$$

where m is the mean value of mass of molecules in atmosphere. Taking into account that the surface of the Earth is

$$S = 4\pi R_E^2$$

and mass of molecule is

$$m = \mu / N_A,$$

where N_A is Avogadro number, we can write

$$N = N_A \cdot P \cdot 4\pi R_E^2 / \mu \cdot g$$

Since the Earth atmosphere consists mostly on N_2 ($\mu_{N2} = 28$ g/mol) and O_2 ($\mu_{O2} = 32$ g/mol) in approximate proportion 3:1, the mean value of μ is 29 g/mol or in SI: $2.9 \cdot 10^{-2}$ kg/mol. Calculations:

$$N = 6.022 \cdot 10^{23}\,\text{mol}^{-1} \cdot 10^5\,\text{N} \cdot \text{m}^{-2} \cdot 12.6 \cdot (6.37\,\text{m} \cdot 10^6)^2 / 2.9 \cdot 10^{-2}\,\text{kg} \cdot \text{mol}^{-1} \cdot 9.81\,\text{N} \cdot \text{kg}^{-1} = 1.08 \cdot 10^{44} \approx 1.1 \cdot 10^{44}.$$

α-3. Efficiency of eye. For detecting a star the human retina should uninterruptedly remember the image of the star. That is the eye should receive from this star at least 7 photons per second. Human eyepiece is about d = 6 mm in the very dark, so the limit of illumination is:

$$7 \text{ photons} / \pi d^2/4 \approx 250\,000 \text{ photons/m}^2 \text{ (very roughly, of course)}$$

It is about 10 000 000 000 / 250 000 = 40 000 less than the illumination from 0^m star. In stellar magnitudes the difference is:

$$\Delta m = 2^m.5 \lg 40\,000 \approx 11^m.5.$$

So the theoretical limit for human eye in the very dark is to see stars of $11^m.5$. Of course, it is quite far from reality. Nobody reported about possibility to see stars fainter than 8^m even in the absolute dark.

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β-3. Eris. Let us at first answer for the question about the "Great opposition". And what does it mean the word "Great"? The Great oppositions appear for the situation when the distance to opposition planet is smaller than during usual (mean) oppositions. In our case it is an opposition when the outer planet is near its perihelion. Now Eris is near its aphelion point. From the value of the semiaxis of the Eris' orbit it is evident that its period is of order of centuries and we may talk about the period of the Great oppositions as "years" (in comparison with "weeks" for the Great opposition of Mars) near after of half revolution of this dwarf planet around the Sun.

The period of Eris can be taken from the table (days should be recalculated into years)

$$T_{Ed} = 204852 \text{ days} / 365.25 \text{ days/year} = 560.85 \text{ years} \approx 560 \text{ years}$$

or found from the the III Kepler law

$$(T_{Ed}/T_E)^2 = (A_{Ed}/A_E)^3,$$

(here and below A means the major semiaxis, T is period, e is eccentricity, α is albedo, D are diameters of the bodies, R are distances, and indexes E, Ed, Sa and S correspond to Earth, Eris, Saturn and Sun).

$$T_{Ed} = T_E \cdot (A_{Ed}/A_E)^{3/2} = 1 \cdot (68.01)^{3/2} \text{ years} \approx 560 \text{ years}.$$

So the years of the "Great oppositions of Eris" will be after $T_{Ed} / 2 \approx 280$ years.

For the questions of the stellar magnitude there may be a few ways to solve this problem. The main two of them is to compare Eris with some other planet (data can be given from the table) or to calculate it directly using formulae of the total solar irradiation.

Let us use the first one and compare Eris and Saturn.

The following aspects should be taken into account:

1. **$R_{S\text{-}>}$**. Distance from the Sun. The intensity of light coming to the bodies is reverse proportional to the square of these distances.

2. **D**. Size (diameter) of the body. The intensity of light reflecting by the body is proportional to the to the square of these sizes.

3. α. Albedo. The intensity of light reflecting by the body is proportional to the albedos.

4. **$R_{E\text{-}>}$**. Distance from the observer (i.e. from the Earth): 1.8 a.u. for the asteroid of the main belt (in oppositions) and about 40 a.u. for asteroid of the Kuiper belt. The intensity of light coming to the telescope is reverse proportional to the square of these distances.

The flux to Earth from Eris $\quad F_{Ed} \sim \alpha_{Ed} \cdot D_{Ed}^2 \cdot (1/R_{E\text{-}Ed})^2 \cdot (1/R_{S\text{-}Ed})^2.$

The flux to Earth from Saturn $\quad F_{Sa} \sim \alpha_{Sa} \cdot D_{Sa}^2 \cdot (1/R_{E\text{-}Sa})^2 \cdot (1/R_{S\text{-}Sa})^2.$

The ratio of fluxes $\quad F_{Ed}/F_{Sa} = (\alpha_{Ed}/\alpha_{Sa}) \cdot (D_{Ed}^2/D_{Sa}^2) \cdot (R_{E\text{-}Sa} \cdot R_{S\text{-}Sa})^2/(R_{E\text{-}Ed} \cdot R_{S\text{-}Ed})^2.$

For the current situation the following distances should be used:

Since Eris is near its aphelion, $R_{S\text{-}Ed} = (1+e)A_{Ed}$, and $R_{E\text{-}Ed} = (1+e_{Ed})A_{Ed} \pm A_E$, but, since we do not know the real configuration of Earth, Sun and Eris (including we do not know the inclination of the Eris' orbit), we should use the average value of $R_{E\text{-}Ed} = (1+e_{Ed})A_{Ed}$ as well.

The stellar magnitude for Saturn is given for the mean opposition, so we should not use eccentricity here, $R_{S\text{-}Sa} = A_{Sa}$ and $R_{E\text{-}Sa} = A_{Sa} - A_E$.

$$F_{Ed}/F_{Sa} = (0.86/0.68) \cdot (2600/120536)^2 \cdot (8.584 \cdot 9.584)^2/(1.434 \cdot 68.01)^4.$$

$$F_{Ed}/F_{Sa} \approx 4.4 \cdot 10^{-8}.$$

So the difference in magnitudes between the current visible Eris and Saturn in mean opposition is

$$\Delta m = -2^m.5 \cdot \lg(F_{Ed}/F_{Sa}) \approx 18^m.4,$$

and the magnitude of Eris

$$m_{Ed} = m_{Sa} + \Delta m = 0^m.7 + 18^m.4 \approx 19^m.1.$$

The real values that can be found in reports of Eris observations are $18^m.7 \div 18^m.8$.

$$F_{Ed}/F_{Sa} \approx 1.91 \cdot 10^{-6}.$$

$$\Delta m = -2^m.5 \cdot \lg(F_{Ed}/F_{Sa}) \approx 14^m.3,$$

and the magnitude of Eris in the "Great opposition" is

$$m_{Ed} = m_{Sa} + \Delta m = 0^m.7 + 14^m.3 \approx 15^m.0.$$

And we should repeat that this way with comparing the Eris and Saturn it is not the only possible correct way for solution.

αβ-4. Catastrophe. At first we should realise that "suddenly decreasing of solar mass to half its original value" is a hypothetic process and many physical laws of conservation cannot be used to compare parameters before and after since the system is not closed. Since no any other changing done, we should assume that at the moment of the mass decreasing other parameters of the Sun and the Earth have not changed: Positions of the Sun and the Earth, velocity of the Earth. Taking into account this postulate, a first approximation, if mass of a central body is reduced to half its original value, the circular speed becomes parabolic one. That is the Earth will move on a parabolic orbit and will never return. The answer to the problem is meaningless (the period is equal to infinity).

Nevertheless, it is known, that on July 5 the Earth is near the aphelion of its orbit. Its speed in this case is less than circular. Thus, in this case if mass of a central body to reduce twice, the speed of the Earth already is less than parabolic, the Earth will be rotate around the Sun on a prolate elliptic orbit.

For the beginning let us find a relation between the speed of the Earth in aphelions V_{aph} and circular speed V_0 for a motion on a circular orbit with the same semi-axis.

Using the II Kepler law one may write

$$V_{per} \cdot R_{per} = V_{aph} \cdot R_{aph}.,$$

using the law of conservation of energy

$$V^2_{per}/2 - GM/R_{per} = V^2_{aph}/2 - GM/R_{aph}.,$$

and also taking into account, that

$$R_{per} = a_0\,(1\text{-}e),\ R_{aph} = a_0\,(1+e),\ GM = V_0^2 \cdot R_0\,,$$

it is possible to find

$$V_{per} = V_0 \cdot \{(1+e)/(1\text{-}e)\}^{1/2}\,,$$

$$V_{aph} = V_0 \cdot \{(1\text{-}e)/(1+e)\}^{1/2}\,.$$

The orbit parameters of the Earth after that the mass of Sun has decreased to half its present value are designate as:

a_N – semi-axis of an orbit,
T_N – period of revolution,
e_N – eccentricity,
V_N – speed for a motion on a circular orbit with a semi-axis a_N.

Let us write three additional equations:

distance R_{aph}., former distance in aphlion, became now the distance in perihelion

$$a_0\,(1+e) = R_{aph} = R_{per\text{-}N} = a_N \cdot (1\text{-}e_N),$$

speed V_{aph}., former speed in aphlion, will now become the speed in perihelion

$$V_{aph} = V_{per\text{-}N} = V_N \cdot \{(1+e_N)/(1\text{-}e_N)\}^{1/2},$$

and the relation

$$V_N = 2\pi a_N / T_N\,.$$

By solving all equations together it is possible to receive a beautiful expression

$$a_N = a_0(1+e)/2e.$$

According to the general III Kepler law

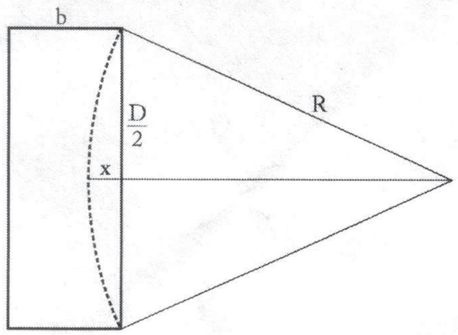
$$T_N = T_0 \cdot 2^{1/2} \cdot (a_N/a_0)^{3/2},$$

one can find

$$T_N = T_0 \cdot 2^{1/2} \cdot ((1+e)/2e)^{3/2},$$

$$T_N = 2^{1/2} \cdot (1.017/0.034)^{3/2} \approx 230 \text{ years.}$$

α-5. Mirror for a telescope. It is evident that the depth '**x**' in the centre of the disc must be less than b = 40 mm. Let R be the curvature radius of the mirror. It means (from the Pythagorean theorem) that the minimum R is defined by the equation:



$$R^2 = D^2/4 + (R-b)^2$$

$$2Rb = b^2 + D^2/4$$

$$R = D^2/8b + b/2$$

The relation between the focal length F and the curvature radius of the mirrow is R = 2F, i.e. for zero thickness in the centre of the disc

$$F = R/2 = D^2/16b + b/4$$

$$F = 500^2/(16 \cdot 40) + 40/4 \approx 401 \text{ mm}$$

So, theoretically the focal length may be in the interval from 401 mm to infinity. Nevertheless, the thickness in the centre of the disc cannot be zero, let us take it at least 2 mm. In this case we should use b* = 38 mm instead b = 40 mm

$$F = R/2 = D^2/16b^* + b^*/4$$

$$F = 500^2/(16 \cdot 38) + 38/4 \approx 421 \text{ mm}$$

The focal length may be in the interval from about 420 mm to infinity.

β-5. Galaxy pair.

5.1. In April and September, the right ascension of the sun is about 0.5-2.5 h and 10.5-12.5 h respectively. And the right ascension of the galaxy is RA ≈ 147° ~ 10h. Thus, April is the better choice because in September the visual position of the galaxies is too close to the sun. Answer: **Apr.**

~ 1 p

According to the DECs of the two galaxies, it's easy to find that the upper one is IC564.

~ 0.5 p

5.2. The wavelength of Hα emission line measured in figure 2 is approximately 6700 Å.

~ 1 p

Taking into account (see table of constants) that the laboratory wavelength of Hα emission is 6563 Å, the redshift of the galaxy is:

$$z = (\lambda - \lambda_0)/\lambda_0 = (6700-6563)/6563 = 0.02$$

~ 1 p

5.3. Since z << 1, the recession velocity of the galaxy is:

$$v = cz = 6000 \text{ km/s}$$

~ 1 p

We should choose the filter whose peak value of redshift is close to 6000 km/s. The suitable one is № C4.

~ 1 p

5.4. According to Hubble's law, the distance to the galaxies is:

$$r = v/H_0 = 6000 \text{ km/s} / 70 \text{ (km/s)/Mpc} \approx 85 \text{ Mpc, i.e. } 85\,000\,000 \text{ parsec.}$$

~ 1 p

The two galaxies are close to each other and the curvature of the celestial sphere can be neglected. The angular distance of the centers of the galaxies is:

$$\alpha = (\Delta RA^2 + \Delta DEC^2)^{0.5}$$

Where, ΔRA = (RA1-RA2) × cos(DEC) = 0.00303°, ΔDEC = (DEC1-DEC2) = 0.02579°. As a result,

$$\alpha = 0.02597° = 93.5''.$$

~ 1 p

The distance between the two galaxies is:

$$d = r \cdot \alpha = 85\,000\,000 \cdot 93.5 / 3600 / 57.3 = 38.5 \text{ kpc}$$

~ 0.5 p