Observational Astrophysics
1. Astronomical Measurements

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1 Introduction

Most of the information that we can gather from astronomical sources arrives to us in the form of electromagnetic radiation, but not only. In addition to photons, astronomical information can be gathered from at least:

- cosmic rays,
- neutrinos,
- meteorites,
- gravitational waves,
- solar wind particles, and
- samples returned from solar system objects.

We might not find the time to discuss all the points above during our lectures. Nevertheless, before the end of the course, I will prepare and provide some reading material about these items.

So, what I am broadly defining here as **observational astrophysics** is concerned with using different "carriers of information" to: i) measure properties from astronomical sources; ii) understand the errors of such measurements; and iii) use what has been measured to estimate parameters that can, in turn, be used to test astrophysical models and theories. Note that I am trying to make a difference between things that can be measured and things that can be estimated from the measurements.

The main focus of these lectures (and of the reading material) will be on methods, tools, instruments, and data related to the observation of electromagnetic radiation. We will mostly talk about the ways (and the hurdles) of obtaining information through observations. The theoretical aspects of the astrophysical processes emitting electromagnetic radiation might be briefly mentioned, but will not be covered in detail in this course.

Ok. Which quantities can be measured from observations of electromagnetic radiation? Below is a (likely incomplete) list (note also that we can not measure all these quantities for every source):

- Position of the source, i.e. two coordinates of the position projected on the celestial sphere;
- Distance to the source, i.e. the third spatial coordinate of the source;
- Size and shape of the source (in case it can be resolved);
- Motion (projected) on the sky (the proper motion);
- Motion along the line of sight (the radial velocity);
- (Projected) Rotation and orientation;
- Flux (i.e. a measurement of the rate with which energy travels through a surface. We will cover what astronomers mean by that below);
- Spectral energy distribution (energy as a function of frequency or wavelength);
- Polarization;
- Acceleration (in certain cases);
- The time variability of (some? of) the previous quantities.

Note however that there is a catch. Mostly, what is measured from the data is not in physical units. In general, the measurements need to be calibrated to eliminate instrumental signature and to convert the "instrumental units" to physical units (e.g., brightness of a star might be measured in "counts/second"; sizes and distances in units related to the pixel size in your detector). Converting the measurements to physical units might require the understanding and modelling of several factors, such as the atmospheric absorption, the transmission of the telescope, and the size and sensitiveness of the detector.

Let's start with some basic definitions needed to study the radiation field.

2 Radiation field

I am going to define the quantities with the common names that are usually adopted in stellar astrophysics, at least when discussing stars that are not very different from the Sun. Usage of names and symbols can vary quite a lot. It is definitely different between astronomers and physicists, and can also vary among different areas of astrophysics (e.g. optical and radio astronomy). The units of choice also vary, mostly because the scales involved can be quite different depending on the type of source and the characteristics of its energy output.

2.1 Luminosity

Luminosity is the rate at which energy is emitted or radiated from a source in all frequencies/wavelengths (therefore, luminosity is, in other words, power). This is sometimes also called the "bolometric luminosity". Bolometric is a word used here to mean a quantity integrated in all frequencies/wavelengths. It comes from the bolometer, a device used to measure the power of incident electromagnetic radiation via the heating of a material. The bolometer can essentially be sensitive to radiation in all wavelengths.

In astronomy, the common symbol for luminosity is L. In physics, the same quantity can also be referred to as "radiant flux" or "radiant power", with symbols Φ or P, respectively.

In the international system of units (SI), luminosity is given in watts (W), which means joule per second (J s^{-1}). Astronomers might also use erg s^{-1} in the centimetre–gram–second system of units (cgs), where 1 erg = 10^{-7} J, or express the quantity in units of solar luminosity ($L_\odot$).

The luminosity of a source can be written as

$$L = A\ S, \tag{1}$$

where A is the area of the source and S is the "flux" of energy radiating out of the source (i.e., the energy rate per unit area – see subsection 2.4 below). As such, it can also be written relative to the flux observed at Earth (F), if we assume that the source is radiating isotropically:

$$L = 4\pi d^2\ F \tag{2}$$

(where d is the distance to the source).

Sometimes, you will find that people can also talk about the "luminosity" in a given wavelength range (or passband). At least for me, encountering that can be quite confusing, but it is common in certain areas. The B-band and K-band luminosities (where B and K are photometric bands) are used in the study of luminosity function of galaxies, for example.

2.1.1 Solar luminosity

Let me make some side comments about the solar luminosity. The value for the nominal solar luminosity currently recommended[1] by the International Astronomical Union (IAU) is $L_\odot = 3.828\times10^{26}$ W. I say currently because, yes, slightly different values have been recommended at other times. This value corresponds very closely to what is measured (within the uncertainties, but keep reading because luminosity is actually not the quantity that is measured). The need to have a nominal value comes from the need to standardize magnitude scales.

By the way, it happens that the Sun is a variable star so its energy output varies with time; remember the 11-year solar cycle? And there are other sources of variability causing changes in different timescales, from minutes, to weeks, to longer (see, e.g., Kopp 2016, if interested)[2].

Moreover, the solar luminosity is not what can be directly measured. That would be what is called the solar "irradiance". Either in the form of "total irradiance" (see point 2.3 below) or "spectral

[1] See `https://www.iau.org/static/resolutions/IAU2015_English.pdf`
[2] `https://ui.adsabs.harvard.edu/abs/2016JSWSC...6A..30K/abstract`

irradiance" (see point 2.4 below). Irradiance is the power received by a surface per unit area (SI units of W m^{-2}). We have "spectral irradiance" when the power is measured per wavelength or per frequency (SI units of W m^{-2} Hz^{-1} or W m^{-3}).

The measurement of irradiance can be done either from space or from the ground. However, if done from the ground one has to correct from the effects of variable atmospheric transmission. Therefore, measurements from space are regarded as more accurate.

The quantity called "total solar irradiance" (TSI) is the solar irradiance normalized to the mean Earth-Sun distance (the astronomical unity; au). TSI has been recorded from space continuously since 1978. The TSI averages to about 1361 W m^{-2} (Kopp & Lean 2011; Finsterle et al. 2021)[3]. The 11-year solar cycle causes a variation of about 0.1% on the TSI value (Kopp 2016).

For completeness, let me digress a bit about the astronomical unit. The recommended value of 1 au has been redefined a few times. Since 2012, the IAU recommends[4] an exact definition where 1 au = 149 597 870 700 m. The $L_\odot$ value quoted above is consistent with this definition of 1 au (see Pitjeva & Standish 2009, and references therein for measurements of the astronomical unit that resulted in the quantity recommended by the IAU)[5].

Note that, to finally move from the TSI (in W m^{-2}) and get the "nominal" $L_\odot$ (in W), we still need to do the spatial integration. So there is another implicit assumption here, i.e. that the solar emission is isotropic. We assume that the amount of energy measured to be going through the small area of the detector in our instrument is representative of the energy going through any other selected region of the larger sphere of area $4\pi(1\text{au})^2$.

Finally, the $L_\odot$ value that was given above is meant to represent the solar output in terms of electromagnetic radiation. It does not include the output in terms of solar neutrinos (which is of the order of $\sim 0.023\ L_\odot$ – this number is usually attributed to calculations by John Bahcall, but I could not find a clear reference...).

Ok, all this long discussion about the solar luminosity was meant to illustrate the observational complications[6] of what should have been a simple concept. It also serves to highlight the difference that I was trying to make between quantities that can be measured and quantities that can be estimated from measurements (TSI $\times$ $L_\odot$). Let's move on (but, if you would like to know more about some current instruments measuring TSI, see point 2.10 below).

2.2 Solid angle

I already mentioned the need of a spatial integration for getting the luminosity. As the definitions of solid angle and spherical coordinates are needed for some of the next quantities, let me formally introduce them as well.

[3] https://ui.adsabs.harvard.edu/abs/2011GeoRL..38.1706K/abstract and https://ui.adsabs.harvard.edu/abs/2021NatSR..11.7835F/abstract

[4] See Resolution B2 of 2012: https://www.iau.org/static/resolutions/IAU2012_English.pdf

[5] https://ui.adsabs.harvard.edu/abs/2009CeMDA.103..365P/abstract

[6] And do not forget that I did not mention any of the hurdles related to processing the data, to go from what is really measured in the detector to the physical quantity we want.

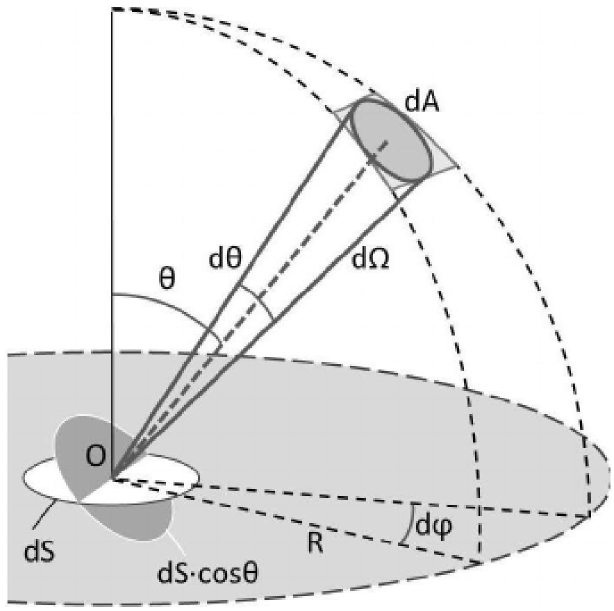

Figure 1: Solid angle and spherical coordinates (image source: `https://math.stackexchange.com/questions/3121489/can-there-be-two-adjacent-solid-angles`).

Consider a sphere of radius R and origin at O (see Fig. 1). The solid angle Ω is the amount of area, A, subtended by an object on the surface of that sphere. That area can have any arbitrary shape.

$$\Omega = \frac{A}{R^2} \tag{3}$$

In the SI, the solid angle is given in a dimensionless unit called a *steradian* (sr). Other possible units include the squared version of angular units, e.g. $\deg^2$; where 1 $\deg^2 = (\pi/180)^2$ sr.

And in terms of the spherical coordinates, we can get a formula for the differential of the solid angle:

$$d\Omega = \frac{dA}{R^2} = \frac{Rd\theta\ R\sin\theta d\varphi}{R^2} \tag{4}$$

$$d\Omega = \sin\theta\ d\theta\ d\varphi \tag{5}$$

2.3 Bolometric flux

In astronomical language, the bolometric flux (F_{Bol}) is essentially the same as the total irradiance defined above (SI units of W m^{-2}; commonly given in erg s^{-1} cm^{-2}). Bolometric flux is the power from the source, arriving at Earth, per unit area, in a surface that is normal to the direction of the energy flow.

One can imagine that complete characterization of the total energy output, from the shortest to longest wavelengths, is something rarely performed for most objects.

In stellar astrophysics, this gave rise to the bolometric corrections (see Section 2.9.3 below), which is a way to obtain the bolometric flux (or actually the bolometric magnitude) from the measured flux in a certain band.

Confusingly, bolometric flux is also sometimes called the total flux. Bolometric flux is the F that one would input in equation 2 to, together with the distance, calculate the luminosity of the source.

2.4 Flux

Ok, so I talked about bolometric flux before introducing what I even mean by flux. Well, flux (F or sometimes S, and sometimes more explicitly F_ν or F_λ) in this case is the same as the spectral irradiance mentioned above (SI units of W m^{-2} Hz^{-1} or W m^{-3}), i.e. the amount of energy received by a surface, per unit time, per unit area, per unit frequency or unit wavelength.

To continue the tradition of confusing names, flux can also be called "flux density" (density in the sense that the measurement is per unit frequency or unit wavelength).

(And more. In the standard usage in radiometry, when the radiation flux is the one incident on a surface, then flux is called irradiance. When it is meant the radiation flux that is emitted from a surface, then flux is radiant exitance).

A unit of flux commonly employed in radio astronomy is the jansky (Jy), where 1 Jy = 10^{-26} W m^{-2} Hz^{-1}. The unit name is in honour of Karl Guthe Jansky, American physicist and radio engineer of Czech roots. In 1932, he was an engineer for Bell Laboratories and was facing a technical problem. Some static noise was interfering with short-wave radio transatlantic voice communications (Jansky 1932)[7]. After tracking the source and noticing the periodicity equal to Earth's rotation relative to the stars (sideral day), he concluded the radiation was coming from the Milky Way, in the direction of the center of the Galaxy in the Sagittarius constellation. A short note about the discovery came out in Nature (Jansky 1933b)[8] and a longer description in Popular Astronomy (Jansky 1933a)[9]. Without really wanting, Jansky had just founded radio astronomy.

2.5 Specific intensity

As far as I understand, specific intensity is a term mostly used in astrophysics. In physics, this would be called spectral radiance. It seems that in radio astronomy this same quantity is called "brightness"[10].

[7] `https://ieeexplore.ieee.org/abstract/document/1685061`

[8] `https://www.nature.com/articles/132066a0.pdf`

[9] `http://articles.adsabs.harvard.edu/pdf/1933PA.....41..548J`

[10] Note that throughout this text material, when I say brightness I am instead trying to be not specific about the meaning. I use brightness just to mean a subjective evaluation of how "bright" something is, without implying a proper definition neither units. Like when we colloquially say that the Sun is brighter than the Moon. Nevertheless, usually what I mean is closer to the definition of flux density.

Radiance is the radiant flux emitted by a surface per unit solid angle, per unit projected area. The spectral radiance is the radiance per unit frequency or wavelength. So, in the astronomical language that I am using, specific intensity is the luminosity (the temporal rate at which energy is emitted) per unit solid angle, per unit projected area, per unit frequency (or wavelength). Its SI units are thus W sr^{-1} m^{-2} Hz^{-1} (in cgs, the units would be erg s^{-1} cm^{-2} rad^{-2} Hz^{-1}).

Specific intensity is the most fundamental of the quantities that characterize the radiation field, because it gives the emitted energy per frequency with respect to geometric (position, direction, area) and temporal quantities.

Consider a radiating surface, of area dA and oriented in a certain direction that has an angle θ with respect to the direction towards the observer (Fig. 2). The surface might be anything like the outer boundary of a star or a certain region inside a gas cloud. The amount of energy, per frequency, emitted per second, in the direction of the observer, into the infinitesimal solid angle $d\omega$ is:

$$\mathrm{d}E_\nu = I_\nu \cos\theta \, \mathrm{d}A \, \mathrm{d}\omega \, \mathrm{d}\nu \, \mathrm{d}t \,, \tag{6}$$

where I_ν is the specific intensity. And we could define it also in terms of wavelength such that: $I_\nu \, \mathrm{d}\nu = I_\lambda \, \mathrm{d}\lambda$.

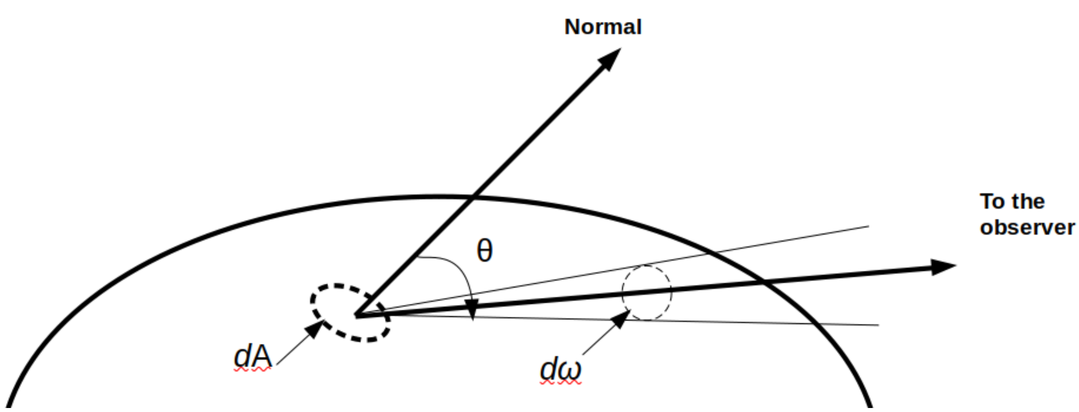

Figure 2: The geometry needed for the definition of specific intensity.

Note that since the specific intensity represents the energy emitted into a solid angle, it is actually independent from the distance to the source. It does not matter to what distance you are from the source, if at different distances you can measure the energy within that same solid angle, the multiple values that you measured would be the same. It follows then, that one can only measure the specific intensity if you can resolve the source (i.e., for sources with a measurable angular diameter) and thus can select the fraction of the source that emits into a certain solid angle. The specific intensity can be measured from different places in the solar disk, for example. If you can not resolve the source, then what you are measuring is the flux, not the specific intensity.

2.6 Intensity

This here is just to say that, most of the time, people drop the "specific" and talk about intensity. So, most of the time when you read or hear about intensity, what is really meant is "specific intensity".

Nevertheless, sometimes, what people mean is actually the integrated specific intensity over all frequencies:

$$I = \int_0^\infty I_\nu \mathrm{d}\nu \tag{7}$$

You should also remember that, in physics, intensity usually means the power per unit area (more akin to our definition of flux). I have seen also the term "radiant intensity" to mean the power per unit solid angle (nothing equivalent to the astronomical quantities defined above), and "spectral intensity" to mean the radiant intensity per unit frequency (what you would get integrating the specific intensity in area).

2.7 Relations between flux, intensity, luminosity

This section is just to bring everything around and connect the above astronomical definitions of flux, specific intensity, and luminosity to each other.

Flux density and specific intensity:

$$F_\nu = \oint I_\nu \, \cos\theta \, \mathrm{d}\omega \tag{8}$$

Bolometric flux:

$$F_{\mathrm{bol}} = \int_o^\infty F_\nu \, \mathrm{d}\nu \tag{9}$$

Luminosity, based on the bolometric flux measured on Earth:

$$L = F_{\mathrm{bol}} \oint \mathrm{d}A = F_{\mathrm{bol}} \; 4\pi \, d^2 \tag{10}$$

(where d is the distance to the source).

And just for completeness, you might sometimes encounter something called the "mean intensity" (J_ν):

$$J_\nu = \frac{\oint I_\nu \, \mathrm{d}\omega}{\oint \mathrm{d}\omega} = \frac{1}{4\pi} \oint I_\nu \, \mathrm{d}\omega \tag{11}$$

2.8 Flux dilution

What is the connection between the flux emitted at the surface of the source (let's call it F_{emitted}) and the flux measured on Earth (F_{measured})?

For simplicity, let's assume here that the source is spherical with radius R. Then the luminosity can be related to the flux emitted at the surface by

$$L = F_{\mathrm{emitted}} \; 4\pi \, R^2, \tag{12}$$

and at the same time we can write the luminosity as a function of the measured flux as seen at Earth, which is at a distance d from the source:

$$L = F_{\mathrm{measured}} \; 4\pi \, d^2. \tag{13}$$

From those two equations it follows that:

$$\begin{aligned} F_{\mathrm{measured}} \; 4\pi \, d^2 &= F_{\mathrm{emitted}} \; 4\pi \, R^2 \\ F_{\mathrm{measured}} &= (\frac{R}{d})^2 \, F_{\mathrm{emitted}} \\ F_{\mathrm{measured}} &= \frac{1}{4} \, \alpha^2 \, F_{\mathrm{emitted}} \end{aligned}$$

Where you can see that the measured flux is always a diluted version of the emitted flux, the value falling with distance squared. The α in the last equation is the angular diameter ($\frac{2R}{d}$).

2.9 Magnitudes

Photometric systems, filters, and colors (and extinction), will be discussed separately in another chapter. Here I will just mention the concept of magnitudes and connect it to luminosities and fluxes.

The concept of magnitudes as we use it dates at least to the Greek astronomer Hipparchus of Nicaea (a Greek city in northwestern Anatolia, which now is actually part of Turkey). He ranked the stars visible to the naked eye on a numerical scale from 1 to 6 (from the brightest to the faintest, respectively). This was thus not exactly a quantitative definition of the magnitude scale, but a subjective one.

The English astronomer Norman Robert Pogson proposed that a fixed ratio of 2.512 be used between the brightness of stars differing by one magnitude (Pogson 1856)[11]. In other words, that a star of magnitude 5 has 2.512 times the "light" of a star of magnitude 6. In his paper, he mentions that other astronomers had proposed different values for this ratio. His own experiments indicated a ratio of about 2.4 between the "brightness" of stars differing by 1 mag. He decided to use a ratio of 2.512 for convenience of calculation. He mentions that in photometric equations the quantity $(\frac{1}{2}\log\ R)^{-1}$, where R is this ratio between the brightness of stars differing by 1 mag, appears quite frequently. So a ratio of 2.512 gives basically an exact value of 5 to this quantity.

In general terms, the magnitude is defined by:

$$m = -2.5\ \log_{10} \int_0^{\infty} F_\nu W(\nu)\, \mathrm{d}\nu\ + \text{constant}, \tag{14}$$

where F_ν is the flux (flux density) of the object and $W(\nu)$ specifies the spectral interval and how much of the flux in each ν is actually recorded by your equipment (this would essentially be the response function of your photometric filter + detector + telescope). And there is an arbitrary zero-point constant. Note that the factor of 2.5 in this last equation is not the rounded version of the 2.512 that I mentioned above. It comes from $\log_{10}(2.512) = \log_{10}(100^{1/5}) = 0.2\ \log_{10}(100) = 0.2 \text{ x } 2 = 0.4 = 1/2.5$.

2.9.1 Bolometric magnitude

The bolometric magnitude is defined on the total energy emitted by the source at all frequencies/wavelengths. Its definition is thus tied to the luminosity:

$$(M_{\text{bol},1} - M_{\text{bol},2}) = -2.5 \log_{10}(\frac{L_1}{L_2}) \tag{15}$$

The point of the IAU in recommending a value for the nominal solar luminosity was to standardize the zero point of the bolometric magnitude scale. With the value mentioned above, the IAU recommends a constant for equation 14, when used with the luminosity, that makes the bolometric magnitude of the Sun become $\mathrm{M}_{\text{bol},\odot} = 4.74$ mag. There was some variation in the bolometric scale used in the literature, which made comparisons among different works uncertain if you were not very careful. This value of 4.74 mag seemed to be the value most commonly adopted in the recent literature and was thus chosen as reference by the IAU.

Note that what I define here as "the bolometric magnitude" is sometimes referred to as "absolute bolometric magnitude", to differentiate it from the "apparent bolometric magnitude", which is related to the definition of apparent magnitude discussed below.

[11] `https://ui.adsabs.harvard.edu/abs/1856MNRAS..17...12P/abstract`

2.9.2 Apparent magnitude

The apparent magnitude is related to how the brightnesses of an object is perceived/measured from Earth. So it is related to the flux density integrated in the band defined by your filter, as in equation 14. If we have two objects where these integrated fluxes are F_1 and F_2, then their apparent magnitudes are related by:

$$(m_1 - m_2) = -2.5 \log_{10}(\frac{F_1}{F_2}) \tag{16}$$

If in equation 14 we make $W(\nu) = 1$ and include the observed radiation in all frequencies (i.e., use the bolometric flux), then we can define the "apparent bolometric magnitude". To reinforce, this is called "apparent" because it is related to how the brightness of an object is perceived from Earth, and not really to the intrinsic amount of energy that the source is outputting. As discussed in Section 2.8, this has to do with the spatial dilution of the flux.

2.9.3 Absolute magnitude

To facilitate the comparison between the intrinsic brightness of different sources, the concept of absolute magnitude was introduced. This is the magnitude that the source would have if it was positioned at a reference distance from the Earth. For stars, this reference distance is usually taken to be 10 pc. For solar system objects, it is usually 1 AU.

For a given star, its apparent and absolute magnitudes are related by:

$$M_{\text{abs}} = m + 5 - 5\log(d), \tag{17}$$

where M_{abs} is absolute magnitude, m is the apparent magnitude, and d is the distance to the source (in parsecs). The quantity $(m - M_{abs})$ is known as the "distance modulus". Note that, traditionally, lower case m is used to indicate the apparent magnitude and upper case M the absolute one.

(to arrive to Eq. , just write equation 2 twice, for the apparent flux and the flux at 10 pc, then use the two relations to substitute the Fs in equation 16).

For stars, you can also relate the absolute magnitude to the absolute bolometric magnitude, using a correction derived from models of the stellar emission:

$$BC = M_{\text{bol}} - M_{\text{abs}}, \tag{18}$$

where BC is known as the bolometric correction. In this way, if the stellar distance is known, the apparent magnitude in a given band can be used to estimate the stellar luminosity.

2.10 TSI and SSI

In this Section, I include some additional information and links about the total solar irradiance (TSI) and the spectral solar irradiance (SSI) measurements, but only for those that got a bit curious.

TSI started to be measured from space in 1978 with the Earth Radiation Budget (ERB) instrument (Kyle 1990)[12] aboard the Nimbus-7 mission. The main goal behind the need of keeping track of TSI and SSI is to better understand the role of the Sun on Earth's climate. The Sun is Earth's main energy source and thus measuring TSI helps to determine Earth's total energy input. Measurements of SSI are used to understand how the atmosphere responds to changes in the Sun's output.

TSI varies at the 0.01% level in timescales of minutes, because of solar convection and oscillations. In the timescale of days to weeks, changes of about 0.1% can be detected, because of variations in solar magnetic activity (e.g. spots). Because of the solar cycle, TSI can be higher to about 0.1% during solar maxima (Kopp 2016).

From what I could find out, there are currently at least three instruments capable of measuring TSI from space:

1. The United States National Aeronautics and Space Administration (NASA) currently operates the Total and Spectral Solar Irradiance Sensor (TSIS-1) mission aboard the International Space Station (ISS). TSIS-1 was launched in December 2017 and began to operate in March 2018. It includes two instruments: i) the Total Irradiance Monitor (TIM)[13] which measures TSI at the outer boundaries of Earth's atmosphere, and ii) the Spectral Irradiance Monitor (SIM, Richard et al. 2020)[14] which measures SSI from 200 to 2 400 nm (which corresponds to 96-97% of the TSI).

SIM "consists of three separate channels that each employ a Féry prism[15] to disperse incoming solar radiation onto four detectors: two silicon photodiodes that measure from 200 nm to 310 nm and 310 nm to 950 nm; an InGaAs photodiode that measures from 950 nm to 1650 nm; and an Electronic Substitution Radiometer (ESR) that periodically calibrates the photodiodes and provides additional measurements from 1650 nm to 2400 nm. The spectral resolution of TSIS SIM ranges from 1 nm in the UV to 35 nm in NIR" (text quoted from Mauceri et al. 2020)[16]. The redundant channels are exposed in different duty cycles and used for long-term degradation monitoring and correction.

TIM uses an ambient temperature active cavity radiometer. These systems absorb sunlight turning the incident radiant energy into thermal energy. The light collected by the cavity is absorbed by the cavity walls. Light that is not absorbed on the first bounce is very likely to hit the cavity wall again resulting in around 99.99% light collection. TIM uses four ESRs to measure the incident sunlight.

[12] `https://ui.adsabs.harvard.edu/abs/1990SPIE.1299...27K/abstract`

[13] A descrition of a TIM design for another mission can be found in Kopp & Lawrence (2005); `https://ui.adsabs.harvard.edu/abs/2005SoPh..230...91K/abstract`.

[14] `https://ui.adsabs.harvard.edu/abs/2020RemS...12.1818R/abstract`

[15] My note: A Féry prism has curved faces that collimates, reflects and refracts incident light.

[16] `https://ui.adsabs.harvard.edu/abs/2020SoPh..295..152M/abstract`

And for completeness a few definitions:

- Photodiode is a device that converts light into an electrical current. When a photon of sufficient energy strikes the diode, it creates an electron–hole pair. The resulting accumulation of charge leads to a flow of current in an external circuit.
- The material of the photodiode defines its properties, as the electrons will be sensitive to light of different energy. Silicon is used beyween 190–1100 nm. Indium-gallium-arsenide (InGaAs) is used between 800–2600 nm.
- ESR is essentially a bolometer where the optical power is measured through heating instead of a photon to electron conversion.
- A bolometer is a detector designed for bolometric measurements, i.e. measurements that are in principle sensitive to all wavelengths. In practice a filter can be used to limit the spectral range. The radiation absorbed by the detector raises its temperature. The electrical resistance in a bolometer depends on its temperature and the change produces a signal. The time duration of the signal is related to the rate at which heat leaks from the bolometer.

TSIS-1 has an expected lifetime of about 5 years. The next mission, TSIS-2, is planned to be launched as a free-flying spacecraft sometime in 2023.

2. The European Space Agency (ESA) operates the Solar and Heliospheric Observatory (SOHO) which was launched in 1995 and is still operational. SOHO orbits the first Lagrange point and has an uninterrupted view of the Sun. The Variability of Solar Irradiance and Gravity Oscillations (VIRGO, Fröhlich et al. 1995)[17] instrument is used to characterise solar intensity oscillations and measure the total solar irradiance.

Two types of active-cavity radiometers are used for measuring TSI. In addition, two three-channel sunphotometers (SPM) are used to measure spectral irradiance centered at 402, 500, and 862 nm with a bandwidth of 5 nm, each (see also Fröhlich et al. 1997, and references therein)[18].

3. China operates the Fengyun-3E satellite which was launched in July 4, 2021. This is the fifth in the Fengyun-3 series of meteorological satellites and is designed to have a lifetime of 8 years. One of the payloads is the Joint Total Solar Irradiance Monitor (JTSIM) which contains the Solar Irradiance Absolute Radiometer (SIAR) instrument. SIAR contains three electrical substitution radiometers, each one with two small conical cavities inside the cylindrical shield. One cavity is the main responsible for the measurements, the other is used for reference (see some discussion about the instrument in Song et al. 2021)[19].

[17] https://ui.adsabs.harvard.edu/abs/1995SoPh..162..101F/abstract
[18] https://ui.adsabs.harvard.edu/abs/1997SoPh..175..267F/abstract
[19] https://ui.adsabs.harvard.edu/abs/2021Ap%26SS.366...27S/abstract

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