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INFRARED THERMOGRAPHY AND THERMOMETRY OF PHOTOTROPIC PLANTS

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Thermal investigations using infrared (IR) thermometry and false colour thermography were carried out on flowering plants in the Botanical Garden of Berlin and in a private garden. Special interest went to phototropic plants that orient their blossoms towards a light source (mainly the sun) and within this group to solar trackers (heliotropism) that follow the path of the sun during the day. Best known among the latter is the sunflower. Bowl shaped flowers comparable to satellite disks focus the solar radiation effectively on their centre, resulting in a warming of the female organs at that point. Temperature differences above ambient can be as high as 10.7 K with a mean value of 6.0 K. Pollinating insects were often observed sun-basking in the bowls or on the flower disks attracted by energetic rewards in form of nectar and heat.

Keywords: *insects, IR thermography, IR thermometry, phototropism, plants*

Introduction

Infrared spectrum

The optical region of the electromagnetic spectrum consists of three parts: the visible (Vis), the ultraviolet (UV) and the infrared (IR). The ‘visible’ part is determined by the limitations of the human eye, which lie at 380 nm in the UV and 780 nm in the IR. These values might be shifted for different animals. Honeybees detect signals between 300 and 700 nm, lacking the far red region of the spectrum, while other animals – rattle snakes or mosquitoes, e.g. – are able to ‘see’ in the near IR. Classical cameras equipped with IR filters and IR sensitive films opened this range for the human observation long ago. Modern digital cameras are often also sensitive in the IR. Commercial IR camera filters transform the obtained pictures into black and white. Very bright tones indicate actively synthesizing plants because of the high reflectivity of their chlorophyll, and more grey tones less active or diseased objects. They thus provide a good opportunity for the evaluation of the status of a plant population. IR photos of the Earth’s surface taken from airplanes or satellites are often presented in false colours (green plants are shown in red) to discriminate environmental disturbances and destructions of soil, forestry or agriculture [1]. Thus, remote sensing became an essential tool in landscape ecology and within it the present technique of IR monitoring [2–4].

IR thermography

The near infrared (800–1000 nm) begins at the upper end of the Vis at 750 nm, followed by the solar reflected IR (1000–3000 nm). The IR investigated and discussed in the present paper concerns the next range, the low end of the mid IR (3000–15000 nm), mainly between 3500 and 5000 nm. This range is described by the Stefan–Boltzmann law relating the spectral radiation density, the emissivity ε, and the 4^{th} power of the absolute temperature T of the object. Thermographic cameras monitor these densities, evaluate them as surface temperatures and transform them into freely selectable colours, usually with black/blue tunes at the low temperature end and red/white at the upper. Temperature can be read to 0.1°C and spatial distances to a few millimetres so that most blossoms may be scanned effectively and pictures resolved with the necessary accuracy. IR thermography is often applied to technical fields like electronics, building insulation [5–8] and human and veterinary medicine [9], while plants were more or less neglected with respect to this technique. Only a few papers have appeared recently [10–14].

Phototropism

Plants are permanently bound to a special location by their roots, so that they have to develop means other than locomotion to reach optimal conditions, preferably enough light, for successful photosynthesis.

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Phototropism is one such means: plants or parts of them like leaves and blossoms orient towards a light source and turn in such a way that a maximum absorbing surface is obtained [15]. The causes of such movements are differences in the photon flux densities of the plant surfaces towards and away from the light. These differences produce a flow of potassium ions to the shaded side, followed by a corresponding movement of water and a diffusion of osmotic compounds. In this way a swelling of the target cells results and a lifting or sinking of the affected organ. These flows are completely reversible when the light direction changes. More information on phototropism and solar tracking can be found in a recent paper of one of the authors [16].

Heliotropism or solar tracking

A special form of phototropism is heliotropism, as described in 'Sunny-side up' and 'Sun Stalkers' by Candace Galen in her papers [17, 18], and which nowadays is called solar tracking, using the sun as light source. The great difference between the two tropisms is that phototropic plants seek a favourable position in connection with the light source and keep it during the day or their life. This may be an orientation towards the zenith, the south, or morning and evening, but also a random distribution of leaves and blossoms around the stem with a suitable inclination (often around 45°) to present a large surface area to the light. In contrast heliotropic plants or their organs turn to the sun and follow its course during many hours per day or even the day around. An astonishing phenomenon with some of the solar trackers is that they give a farewell to the afternoon sun in the west, turn during the night and expect it back in the morning looking eastward to the point where the sun will arise above the horizon. Under constant sunlight north of the polar circle some blossoms (e.g. the Arctic Poppy *Papaver radicatum* [19]) track for 24 h to collect as much energy as possible in the short growth periods in arctic regions. Although bowl-shaped blossoms are frequently found in heliotropic plants (e.g. the Mountain Aven *Dryas octopetala*, *D. integrifolia*, the Arctic Poppy *P. radicatum* and the Snow Buttercups *Ranunculus alpestre*, *R. adoneus*), flat disks are often seen also (e.g. Sunflower *Helianthus annuus*) [14].

Pollinators

Due to their sessile life style, plants are not able to mate directly, but depend on some means of pollen transport from one individual to the receptive female organs of another. Vectors of transport are wind, birds, bats and – especially important – flying insects like honeybees and bumblebees. But such pollinators expect a reward for their flower-visiting. Easily harvested nectar and pollen are welcome, also floral fruit bodies that they can eat during their visits. A further reward in phototropic and solar tracking blossoms is heat: insects experience a favourable microclimate over (disk) or in a blossom (bowl) with a protection against wind and an increased temperature in cold environments.

After a recent paper about the application of IR thermography for general field investigations in a botanical garden [14], we want to concentrate here on its use for a special group of plants that take energetic advantage of phototropic orientation and heliotropic movement and of the specific forms of their blossoms. Such characteristics are known for numerous plants, but the most impressive ones are found in arctic and alpine regions, in deserts and during the weeks of early spring.

Experimental

Materials and methods

Plants

Plants were investigated in the Botanical Garden of the Free University of Berlin and in a private garden between March and October 2005. Sessions were principally performed on sunny days because of phototropism and solar tracking. All IR thermographic pictures were accompanied by conventional photos of the same object in the visible range. More than 50 individual objects were monitored, often together with insects visiting them [14]. In many cases blossoms were artificially shaded after a first IR picture in full sun and photographed again to estimate their rate of cooling.

IR thermography

An IR thermographic camera with a focal-plane array of 256×256 detector elements (Pt–Si–Schottky diodes) and equipped with a Stirling microcooling device was used for the present investigations (Inframetrics SC1000, FLIR Systems, Germany). It worked in the spectral range between 3.5 and 5 μm. Both, the 'Auto Span' mode and the 'Span' mode were applied to see the full range of temperatures within the frame or to set the output just to the botanically interesting range. One has to keep in mind that all non-metallic surfaces have a high absorptance in the mid IR spectrum. Thus, the emissivity is also high and independent of the colour registration one receives in the Vis range. As a good approximation, all plant objects may be assumed to be black bodies with an emissivity near to 100%. Therefore, an emissivity of ε=0.95 was set for all photos, as is usual with plant investigations. The original thermography data (as tif-files in the 'Iron' mode) were imported into Adobe Photoshop 7.0. Colours in the picture were compared with those in the right-hand temperature scale by means of the eyedropper tool and the Navigator Info. In this way, temperatures could be determined to 0.1°C for each point on a blossom. The spatial resolution of the curves (about 70 kpixels) is of course much smaller than that in optical pictures (several Mpixels). Nevertheless, the essential structures of a flower can be easily seen.

IR thermometry

A handheld IR thermometer (THI 300, Tasco/Japan) was also applied with a temperature range between below zero and 200°C and an emissivity ε set to 0.95 as above. Blossoms were scanned by hand for essential points, often repeatedly, to find short-time changes with passing clouds or visiting pollinators. The determined temperatures were noted and later inserted into Vis-photos of the blossom (e.g. Fig. 3).

A long-time continuous monitoring of solar-tracking was not possible with the available thermographic equipment and not intended, as the effect is well known. The interest focussed on the maximum temperature differences between the ambient air or parts of the plants (leaves, stems, e.g.) and the centre of the blossom and its petals. Moreover, IR thermometry could be easily performed over the whole day.

Results and discussion

General observations

Many plants turn their flowers – if possible – towards the sun to make use of better illumination and thus visibility for pollinators and increased temperature for ripening. But when a plant has many flowers it is more advantageous from an energetic point of view to distribute them around the periphery and not to concentrate them on the sunny side only. Nevertheless, some effects of phototropism are manifested also; and more with the leaves than with the blossoms. The two well-known compass plants *Lactuca serriola* (Prickly Lettuce) in Europe and *Silphium laciniatum* (Compass Plant) in North America are examples for this. In the present thermal investigation we concentrated on blossoms oriented towards the sun, whether phototropic in the strict sense or not.

Phototropic plants

The American Prairie Compass Plant *S. laciniatum*, an up to 3 m high perennial with large yellow blossoms found in southern parts of North America, is phototropic in its leaves. Each leaf is a flat lobed sheet turned to a strictly vertical position. Moreover, these leaves frequently orient with their surfaces East-West permanently, pointing with their midrib to the South so that they may be used as a compass in overcast days. This orientation brings two advantages for the plant: a maximum photon flux in the morning or later afternoon no danger of overheating and high water consumption for cooling at noon. Even under Central European weather conditions the differences between experimental orientations perpendicular or parallel to the solar beams can be considerable, amounting to several degrees (not shown). The round leaf-stalks, partly exposed to the sun, were found at 26.7°C, while the leaf-blades remained between 20.5 and 21.6°C at an ambient temperature of 21°C. The flowers of *S. laciniatum* are often evenly distributed around the periphery. Thus, not all are able to become phototropically active, but those on the more southern side orient towards the sun. These bright yellow flowers (Fig. 1a) attract honey- and bumblebees, but other insects are also found in its blossoms. Figure 1b presents a corresponding IR thermographic picture of the temperature distribution with minimum and maximum values of 20 and 27°C, resp. Petals are at rather high tem-

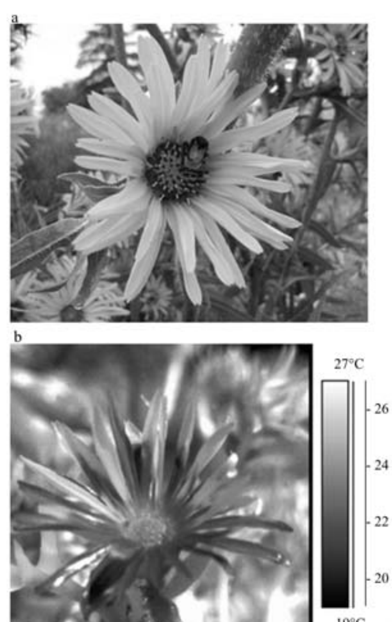

Fig. 1 American Compass Plant (*Silphium laciniatum*) in the Botanical Garden of Berlin, a – seen in the Vis range. Please notice the different orientations of the flower heads in the background. The blossom is visited by a bumblebee (*Bombus lapidarius*). b – photographed by means of an IR thermography camera

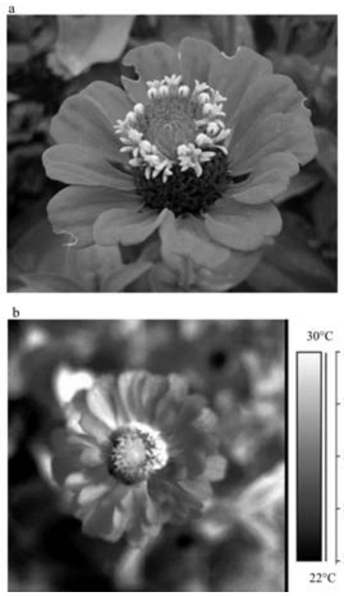

Fig. 2 Garden Zinnia (*Zinnia elegans*), a typical summer flower in our gardens, a – shown in the Vis range. b – IR thermography of a similar blossom. The black parts at the lower left side are significantly cooler than 20°C

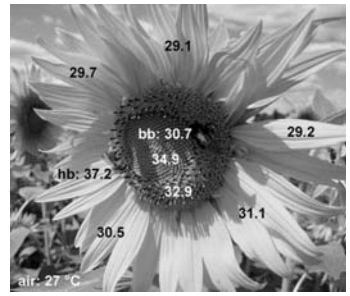

Fig. 3 Sunflower (*Helianthus annuus*) in full sun short time after noon. Temperatures determined with a handheld IR thermometer are indicated in the blossom. 'hb: 37.2' shows the thorax temperature of a honeybee (*Apis mellifera*), 'bb: 30.7' that of a bumblebee (*Bombus lapidarius*). The bumblebee dropped its body temperature by about 7 K, while the honeybee keeps its flight temperature and hurries from floret to floret (bee maxim: Time is honey!)

peratures, while the centre remains around 23.8°C. The Garden Zinnia (*Zinnia elegans*) is a beloved plant of our summer gardens, appearing in a broad spectrum of colours and colour combinations (Fig. 2a). Its IR temperature spectrum ranges from 22.1 to 30.0°C with a high value in the cylindrically formed brown receptacle and medium values in the ring of bright ray florets around the darker disk florets (Fig. 2b). Ambient temperatures are around 21°C.

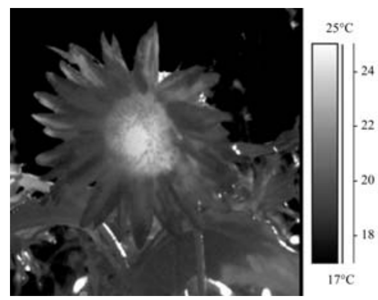

Fig. 4 IR thermography of an old, no longer sun-tracking Sunflower (*Helianthus annuus*) head irradiated from behind. The colours of the scale show that the temperatures are significantly lower than under a frontal illumination

Solar trackers

It is always impressive when one passes – with the sun at the rear – a field of young, blooming Sunflowers. Thousands of heads are looking at you. They are turning with the sun to collect as much heat as possible. Not so the old flowers: they keep an East/North-East orientation to protect the germinating pollen and the seeds against overheating [16]. In Fig. 3 a Sunflower (*Helianthus annuus*) is seen in the early phase of blooming, visited by a honeybee (*Apis mellifera*, hb: left) and a much bigger bumblebee (*Bombus lapidarius*, bb: right). Temperature values determined with the IR thermometer are indicated in the picture, varying by 6°C from about 29°C in some of the petals to about 35°C in the centre of the blossom with its hundreds of small florets. The special surface structure of the centre facilitates higher photon absorption and thus warming up. The bumblebee on the right has already cooled down after landing on the flower, while the honeybee is still at flight temperature, typical for bees that hurry to about 100 flowers during one foraging flight and seldom rest. The shades of the central part indicate that the blossom is not perfectly oriented towards the late noon sun but that some time lag occurred (compare with Fig. 5). IR thermography of an old, no longer tracking Sunflower (Fig. 4) shows a similar temperature variation between petals and centre (18.6 to 24.3°C), but at a lower level than before.

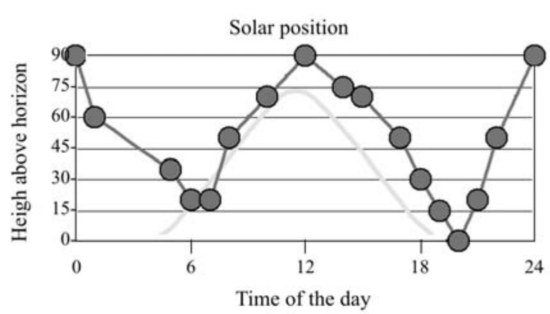

Fig. 5 Inclination of the blossom disk of wild Sunflowers (*Helianthus annuus*) (filled circles) compared with the sun height above the horizon (smooth line). It is evident, that the blossoms tightly follow the sun. Blossoms are oriented in the morning to the East, in the afternoon to the West. (Adapted and modified after [23])

The head looks away from the sun and its face is in the shade. The different air temperatures in both figures are not responsible for the effect: the back of the blossom and the stem are at much higher temperatures because the sun directly hits them.

Heliotropism in the more general meaning of the modern word phototropism has been known since the days of Greeks and Romans, but more often described in poetry and prose than in scientific literature. The last century brought a deeper insight into the phenomena connected with phototropism, and the last fifty years an increased electronic elucidation of heliotropism as solar tracking. Arctic and alpine plants as well as some desert species, all living in harsh conditions, and early-spring flowers as counterparts from temperate regions, attracted special attention if their blossoms were bowl shaped like parabolic mirrors or modern satellite disks. Typical attributes of heliotropic plants in arctic or alpine regions are large petals and parabolic blossoms to concentrate the radiation in the gynoecium, which is placed in the optical focus of the bowl. Although heliotropism is frequently found in *Leguminosae* (e.g. lucerne/alfalfa, lupines, beans and soybeans) and *Malvaceae* (e.g. cotton, desert fivespot), and research was performed on tracking leaves, it is by far more spectacular and interesting with flowers, so that we will concentrate on them.

Heliotropic plants may gain four advantages from the absorbed heat: (*i*) quicker development and maturation of the blossom and the pollen, especially in areas where the growth period is short and the conditions unfriendly [17–22], (*ii*) more frequent and longer, extended visits by pollinators [21], (*iii*) a special attraction for pollinators as they receive extra energy, keep higher temperatures and an increased rate of metabolism and a saving of their own energy reserves [21, 23], (*iv*) a quicker maturation of ovaries of the visitors and thus a further reward for them [21].

The Mountain Avons *Dryas octopetala* and *D. integrifolia*, at home in alpine and arctic regions, are well known solar trackers with beautiful white blossoms. North of the polar circle *Dryas* shows solar-tracking mostly around noon on sunny days with temperature increases of about 2 K in the gynoecium [17–21]. In the Berlin Botanical Garden we found temperature gains of up to 3.7 K in the focus of the bowl [14]. Kevan showed that poppy blossoms (*Papaver radicatum*) track the sun for 24 h in the arctic summer with maximum temperature excesses of 7 K [19]. It was reported that arctic mosquitoes remained fivefold longer in the parabolic blossoms of *D. integrifolia* than was necessary to feed on nectar to repletion and even in the somewhat larger blossoms of *P. radicatum* (+5.8 K) that offer no nectar reward at all. The temperature increases amounted to 3.6 and 5.8 K, resp. The time spent in the blossom supports survival in an environment 'where every calorie counts' [21]. *Oritrophium limnophilum*, a composite with strongly heliotropic stalks growing in high altitudes (~3550 m) of the Andean Pàramo, bends its yellow/white parabolic flowers towards the Sun. Under clear weather conditions temperature increases of up to 6.6 K and frequent pollinator visits are registered, while under hazy sun the effects are reduced or even missing completely for cloudy conditions [22].

One of the best solar tracker is the Sunflower *Helianthus annuus* often cited for this effect. Figure 5 is a graphic adaptation of a table published more than 100 years ago: the orientation of a wild Sunflower population in Kansas [24]. The filled circles show the inclination angle against the horizon of the flat Sunflower blossoms, the second solid line the course of the sun during that July day 1897. The compass orientation of the blossoms was just given as East for 5 am till noon and West for noon to 7 pm in the table. The graph demonstrates impressively how the blossom tracks the sun during the day, but with a retardation of about two hours in the afternoon. When the sun disappears below the horizon, the blossom returns to an upright position at midnight (blossom plate horizontal) and then bends downwards to welcome the sun in the right direction and under a nearly correct angle.

To fully estimate solar tracking and the interplay between plant and pollinator it is necessary to take energy balances into account. The amount of nectar a visitor can obtain in a blossom and its energy value (the 'sugar value') have to be compared with the energy gain by radiation and the heat loss by cooling while sitting on a blossom, to understand if heat is a true reward for a visitor. Insects need high muscle temperatures to fly, which may be derived from internal sources, from food or from radiation. Confounding parameters are nectar production, distance between flowers, competitors, ambient temperature and weather in general. Such energetic aspects of heliotropism – for the plant as well as for the pollinator – will be discussed in a forthcoming paper.

Conclusions

The results of this paper show that IR thermography and thermometry are interesting tools for plant investigations. Contact-free monitoring of leaf and flower surfaces is possible without any disturbances, especially important when visiting pollinators are concerned. Thermography cameras are still very expensive, while handheld IR thermometers became popular in recent years and are easily available. Possible experiments may aim at blossom architecture in connection with energy, microclimate in, above or around the flower, temperature increases and/or nectar production. Moreover, it would be interesting to compare plants in their natural habitat (arctic, alpine or in a desert) with their counterparts in a botanical or private garden under optimal growth conditions.

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