# Motivation and possibilities of affordable low-frequency radio interferometry in space

## Applications to exoplanet research and two instrument concepts

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**Abstract.** The motivation to build spaceborne interferometric arrays for low-frequency radio astronomy is widely recognised because frequencies below the ionospheric cutoff are inaccessible for ground-based radio telescopes. We discuss the theoretical possibilities to use low-frequency spacecraft arrays to detect signals from magnetized extrasolar planets, including earthlike ones. A major uncertainty that prohibits us from knowing if it is possible to detect exoplanet cyclotron maser signals is the incomplete knowledge of the properties of the interstellar plasma. We also present some ideas of how to construct efficient and affordable space-based radio telescopes. We discuss two possibilities, a log-periodic antenna in the spin plane and a two-spacecraft concept where one spacecraft holds a large parabolic wire mesh reflector and the other one contains the receiver. In the latter case, the effective area could be of the order of 1 km$^2$. The purpose of the paper is to stress once more the importance of spaceborne low-frequency measurements by bringing in the intriguing possibility of detecting earthlike exoplanet radio emissions and to demonstrate that building even very large low-frequency antennas in space is not necessarily too expensive.

**Key words.** radio astronomy in space – antenna construction in space – exoplanets

## 1. Introduction

Because of the existence of ionospheric plasma, radio frequencies below 10-30 MHz are difficult or impossible to study using ground-based radio telescopes, whereas low-frequency space-based interferometric arrays with good angular resolution have not yet been built. There are many interesting phenomena to study by low-frequency radio astronomy. This has been pointed out in many references, e.g., Basart 1997b and Kassim and Weiler 1990. These references also give comprehensive lists of radioastronomy research topics for low-frequency space interferometry, which will not be repeated here. Additionally, activities have started lately to make the first radio measurements of extrasolar planets (exoplanets). A more detailed investigation of this is a subject of this paper (section 2 below). Before going into the details of radio detection of exoplanets, we list briefly the principal possibilities to study exoplanets in general (Clark 1998, for recent short review, see Schneider 2002):

1. Detecting the planet-induced wobbling motion of the parent star from the Doppler effect it induces in its spectral lines (Mayor and Queloz 1995). The method gives estimates for the mass and orbiting distance of the planet. This is the primary method for detecting new exoplanets at the moment.
2. Detecting the wobbling motion astrometrically (Benedict et al. 2002).
3. Observing transit situations where the planet moves in front of the parent star and produces a small change in the light curve of the star (Henry et al. 2000, Charbonneau et al. 2000). One can find the orbiting distance and the planetary radius by this method, and in principle also obtain information about the atmospheric composition of the planet. The method requires that the orbital plane is favourably aligned, so it cannot be used for systematic searches in the local neighbourhood.

4. Using gravitational microlensing events caused by remote exoplanets (Bennett and Rhie, 2000). This technique has the potential of providing statistics of exoplanet orbital distances and masses in the galaxy.

5. Direct observation of a nearby exoplanet in visual or infrared (the DARWIN mission, http://sci.esa.int/home/darwin/index.cfm, Fridlund and Kaltenegger 2002). Like the transit technique, this method gives the size and orbital distance, and in its more sophisticated forms also information about the composition of the exoplanet atmosphere. It allows for a systematic study of all exoplanets in the local neighbourhood.

6. Optical or infrared observation of an exoplanet with the help of diffraction at the dark limb of the moon (Richichi 2003).

7. Direct observation of the exoplanet's radio signal. This will give the magnetic field of the planet. Like the visible and infrared direct observation, the method is suitable mainly for nearby exoplanets.

The last method listed is the one elaborated on this paper. It is the only method capable of giving information about the exoplanet's magnetic field and it has not been as extensively developed as some other methods. When combined with direct infrared or optical methods it allows us to study a given exoplanet more closely than with the other methods mentioned. In section 2 we discuss the theoretical possibilities for exoplanet radio detection and in section 3 we discuss two possible affordable but powerful antenna configurations in space. We close the paper with a summary.

## 2. Exoplanet cyclotron maser emissions

In the radio frequencies there have been a few attempts to detect the cyclotron maser emissions from giant gas exoplanets (Winglee et al. 1986, Bastian et al. 2000, Zarka et al. 1997), although no exoplanet radio signal has yet been detected. These searches were ground-based and thus they were limited to frequencies above the ionospheric cutoff. Actually, the frequencies used thus far have been quite high: for example the lowest frequency used by Bastian et al. (2000) was 74 MHz (the highest frequency at Jupiter is 39.5 MHz). The same frequency was probed with 0.12 Jy sensitivity again in 2002 with no exoplanet detected (Farrell et al. 2003).

In Earth's case, the cyclotron maser emission is called the auroral kilometric radiation (AKR) and its frequency range is 50-800 kHz (Gurnett 1974), i.e. much lower than the ionospheric cutoff of $\sim 10$ MHz. The total AKR power emitted by the Earth is $10^7 - 10^8$ W on the average (Gallagher and Gurnett 1979) and $10^9$ W during intense magnetic storms (Gurnett 1974, 1991), which means that AKR power is of the order of one percent of the particle precipitation power. The peak AKR power is therefore about $2 \times 10^8$ times less than the total solar radiation power incident on the top of the atmosphere ($1.7 \times 10^{17}$

W). Due to the radiation balance, the latter number, $1.7 \times 10^{17}$ W, is equal to the total power that the Earth radiates away in infrared; thus the maximum outgoing AKR power is $\sim 2 \times 10^8$ times smaller than the outgoing visible and infrared radiation. As the energy of a photon is inversely proportional to its wavelength, the energy of an AKR photon (typically 3 km, corresponding to 100 kHz) is $3 \times 10^8$ times smaller than the energy of a typical infrared photon emitted (10 $\mu$m, corresponding to 300 K). Since the number of radiated photons per time is equal to the output power divided by the photon's energy, the maximum number of AKR photons is likely to be comparable to the number of photons emitted in the infrared. The infrared emission has been proposed to be used for possible detection of earthlike extra-solar system planets (exoplanets) using interferometric techniques. As an example, if an earthlike exoplanet is at 10 parsec distance and it radiates 100 kHz photons with 1 GW power, the AKR photon flux is $1.5 \times 10^{37}$ s$^{-1}$. In one second, $\sim 10^7$ of these photons pass through a one square kilometer area near the Earth.

The photon count estimate thus shows that in principle, receiving auroral radio emissions from an earthlike exoplanet should be possible and not more difficult than receiving its infrared signal. If a radio signal from an earthlike exoplanet would be received, it might significantly increase our knowledge of such planets in general, because the frequency of the emission is the electron gyrofrequency ($f/$Hz $= 28B/$nT) and we can thus get knowledge of the magnetic field at the bottom of the planet's auroral acceleration region, thus giving a lower limit for the surface magnetic field (Wu and Lee 1979). How quickly the emission varies in time reflects the time constant of the substorm cycle (substorms occur at unpredictable and quasi-random times, but the number of substorms over a long enough observation period should depend only on the aevarge properties of the solar wind and the size of the magnetosphere), which is related to the size of the magnetosphere. At least if the exoplanet is sufficiently earthlike, it should have an identifiable substorm cycle. If a planet has a significant internal magnetic field, it must be produced by a dynamo working in a liquid core. The dynamo action needs a Coriolis force to work, thus the presence of a magnetic field tells that the planet is rotating fast and that it has a liquid core. If the planet is otherwise earthlike and with suitable surface temperature (Franck et al. 2000), these conditions increase the likelihood that it could have conditions suitable for life. Fast enough rotation keeps the day/night temperature difference within reasonable limits and the presence of a liquid core is necessary, although not sufficient, to have plate tectonics to work (Bostrom 2000). Plate tectonics is, on the other hand, probably required to recycle carbon back into the mantle and thus prevent a runaway $CO_2$ greenhouse effect that would turn the planet inhabitable (Gonzales et al. 2001, Franck et al., 1999, 2000). Thus, measuring the radio emissions could be a way to investigate if a planet which is known to be roughly earthlike from other mea-

surements is indeed habitable, or even to make such a judgement without being able to detect the planet at all by other means.

There are two principal difficulties in detecting exoplanet radio signals:

1. Interstellar and interplanetary plasma distort the radio waves, limiting the maximum angular resolution that can be reached (Linfield 1996). If the angular resolution is not good enough, the exoplanet's radio signal is lost in the diffuse background emission, independent of how large radio telescope is used. The amount of diffuse background emission is, however, essentially unknown: what is known is a very low angular resolution map (Brown 1973) and it is not known to what extent the map comes from truly diffuse emissions and to what extent localised sources. If it comes from localised sources, the possibilities for detecting exoplanets increase correspondingly. The only way to find it out is to build a spaceborne low-frequency interferometer.

2. The maximum angular resolution set by the interstellar plasma is in any case almost certainly worse than what would be required to separate the planet from its parent star. Thus in practice the whole stellar system will be seen as one point source. If the parent star or the giant planets outshine the earthlike exoplanet in the radio frequency used, detecting the planet's own signal may then be difficult. However, during certain times even the Earth's AKR may outshine the radio emissions of the Sun so this is not necessarily a problem. For cyclotron emissions of Jupiter-like exoplanets the problem is less severe anyway. It means, however, that attention must be given to methods to distinguish planetary and stellar radio emissions. One way to help distinguishing them is that planetary emissions are circularly polarised while the stellar emissions are not.

To make progress towards solving both problem areas, new high sensitivity and high angular resolution measurements are needed. These are only possible to obtain using spaceborne low-frequency interferometers.

Even if these studies should show that it is not possible to detect earthlike exoplanets due to one of the problems listed above, these new instruments would greatly contribute to the ongoing search for radio signals from gaseous exoplanets. The reason is twofold. Firstly, a much better sensitivity can be expected for a spaceborne interferometer than for ground-based telescopes. The sensitivity mainly depends on the baseline, which can be selected according to the requirements (see also section 3.4.). The radio flux density at the Earth is estimated by Farrell et al. 1999. Secondly, the ionospheric cutoff can be avoided. The maximum frequency emitted by a planet is equal to the gyrofrequency on the planet's surface. Planets orbiting their host stars in very close orbits (i.e. $d \leq 0.1$ A.U.) are subject to strong tidal dissipation, leading to gravitational locking. For such planets the rotation period equals the orbital period, and fast rotation is not possible. Commonly

employed scaling-laws for the planetary magnetic moment (see, e.g. 1995) which are usually based on an $\alpha\omega$-dynamo always yield a magnetic moment rapidly decreasing with increasing rotation period. This puts the expected emission frequencies of several planets (51 Peg, $\nu$ And, 55 Cnc) well below ionospheric cutoff 1999. Furthermore, as the emitted flux density decreases with increasing frequency, even those planets which do emit at higher frequencies will be easier to detect at lower frequencies 2002.
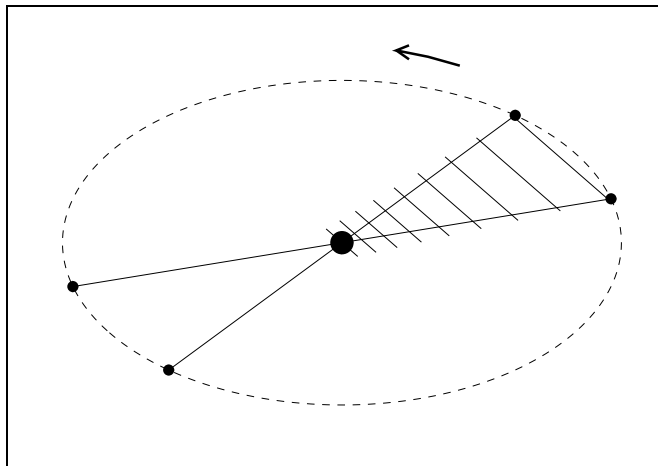
## 3. Low-frequency antenna design in space

A lot of work has been done to design a low-frequency array in space under the ALFA project (Jones et al. 2000). While this body of work provides useful background information, we shall take a fresh approach which takes into account exoplanet detection and recent developments in space technology. This is the reason why the technical solutions we will come up with further below are different from those proposed in the ALFA project.

To reach good angular resolution at low frequencies, interferometry with multiple spacecraft is needed, while the number of spacecraft should be kept at minimum to make the mission less expensive. To increase the ability of the system to observe faint sources, either the number of interferometric measurement points (spacecraft) can be increased or the antenna on each spacecraft can be made more directing. In this paper we especially concentrate on the latter option because it appears more promising in terms of cost-effectiveness. We shall also assume that a rather wide frequency band (e.g., 0.3-30 MHz) must be covered; this precludes designing the antennas specifically for one frequency.

In order to be practical and affordable, at least the following technical requirements must be met. The total mass of the antenna must not exceed a few hundred kilograms. The antenna must be such that it can be packed densely during launch and deployed in space. The construction must not be overly sensitive to micrometeor damage. The length of stiff structures must be kept below a few tens of meters.

Based on these requirements, we considered and rejected many design ideas. A simple dipole wire antenna is technically easy to deploy and is very lightweight (the mass of one kilometre of wire can be made as small as $\sim 1$ kg). For wavelengths larger than the dipole wire length, a dipole antenna works well. For shorter wavelengths the gain pattern becomes complicated and the effective area is of the order of wavelength squared. Thus by using a set of independent dipoles of different lengths (lengths e.g. scaling like powers of two), a wanted frequency range can be covered. This may not be too bad in terms of effective area, but a drawback of dipoles is that they are hardly directing at all. In theory, directing antennas are not needed since a similar effect can be produced digitally if the number of measurement points is large enough, but in practice the finite dynamic range of A/D converters makes it impossible to detect very faint source in the presence of strong radio
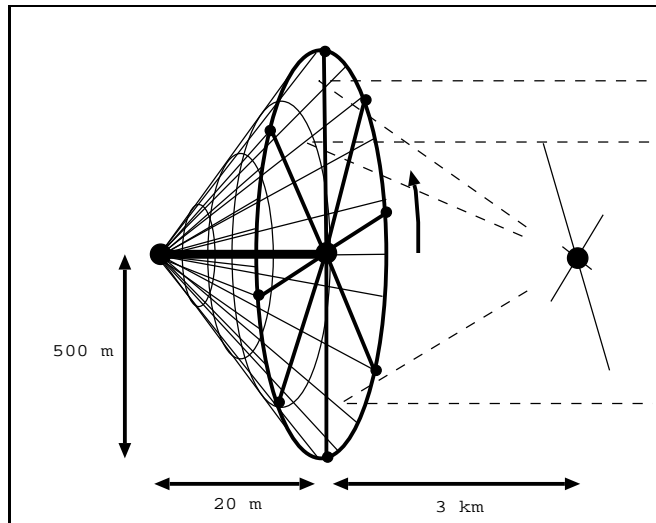
**Fig. 1.** Log-periodic antenna in the spin plane



**Fig. 2.** Two-spacecraft "spidernet" reflector and receiver in space. Here the reflector is shown as conical for simplicity. Support threads and drawn with thicker line than the reflecting spidernet wires. The figure is not to scale.

"noise" from Earth's AKR, Jupiter and the Sun unless the antenna elements themselves are also directing.

The surface of a large gas-filled balloon could be used as an antenna or a spherical reflector, but such a construction is vulnerable to micrometeors (the gas would escape through the holes made by the meteors). A spinning disk-shaped thin mylar or kapton membrane (dielectric) with conducting antenna patterns wired on it is too heavy even if made from 1 $\mu$m membrane. Frequency-independent spiral-shaped wire antennas could be periodically realised in the spin plane by adjusting the spin rate of the spacecraft periodically, but their directivity and effective area is not so much better than those of a simple dipole wire antenna that the extra technical effort involved would be warranted. A Yagi-Uda antenna can be made very directing, but its frequency range is too narrow to be useful.

### 3.1. Planar log-periodic spin-plane antenna

Figure 1 shows a log-periodic wire antenna in the spin plane, spanned by rotating masses. The antenna itself is only on one side of the spacecraft, but for mechanical stability, masses are added on the other side as well. The radius of the dashed circle should be $\sim$ 2 km (the length of the outermost antenna wire should be one half the longest wavelength wanted). Deploying such a system is more complicated than deploying ordinary dipole antennas, but should not be too difficult. The thin antenna wires are stretched between the radial support wires which are kept in shape by the rotating masses. For optimal operation the antenna wires should have a definite thickness which depends on their length (Balanis 1997). Using such thick wires is out of question, but a similar effect could probably be obtained without increasing the antenna mass by using thin conducting bands. A band is also expected to be more micrometeor-resistant than a wire since a meteor only punches a hole in it but does not break the band like it breaks the wire in case of a hit. Thus the meteor danger should not prohibit the use of kilometer-long wires. The feasibility of deploying and maintaining

long wires has also been demonstrated in practice. A 20 km long tether has been almost sucessfully deployed from the Space Shuttle in 1996, although the tether broke due to ohmic heating produced by an induced current in the near-Earth high magnetic field (high induced currents occur only at low Earth orbit where the magnetic field is large). Furthermore, the IMAGE satellite has flown with 500 m tip-to-tip booms for two years now (Burch 2003).

A log-periodic antenna operates well over a wide wavelength range determined by the minimum and maximum length of the antenna rods. The directivity of a log-periodic antenna is usually 7-10 dB (Balanis 1997). For a maximum wavelength of 600 m (500 kHz) the antenna length should be $\sim$ 2 km (the exact length depends on the amount of directivity and on the frequency range), having a total amount of wire of $\sim$ 10 km. A 0.4 mm diameter wire with aluminium mass density (2700 kg m$^{-3}$) has mass per length of 0.34 kg/km so the total mass of wires would be a few kilograms. Even together with the rotating masses that keep the support wires stretched, the antenna mass would remain well below 100 kg.

The object to be measured with a spinning log-periodic antenna should be in the spin plane and useful data of that object can be taken only a short period during each spin. The effective area of a log-periodic antenna is similar to an optimal dipole at each frequency so the chief benefit of the log-periodic construction is its directivity.

### 3.2. Parabolic "spidernet" reflector with two spacecraft

It is not possible to increase the effective area of an antenna element much beyond the square of the wavelength without using a collector, which must be some type of a parabolic reflector in practice. A parabolic reflector has a very good directivity and an effective area which is roughly

equal to its physical area. It works for wavelengths shorter (preferably: much shorter) than its radius.

A circular disk made of wires (a "spidernet", Fig. 2) can be kept in shape by spinning, and it acts as a reflector for waves whose wavelength is longer than the wire mesh spacing. To collect the radiation, however, the dish must be bent, which necessitates a long (half the dish radius) solid axis. For example, if the dish radius is 500 m, the solid axis should be 250 m long. Constructing such a solid axis and deploying it in space is a technological challenge, although probably not impossible since the force that the axis has to withstand is not large.

The length of the required solid axis required to support the parabolic dish decreases if the dish is made more planar, but then the focal point moves away from the spacecraft. Using two spacecraft, one holding the reflector dish and the other hosting the receiving antenna looks more promising, however. For example, with a 20 m long solid spinning axis one can keep in shape a parabolic dish of 1 km diameter. The focal point (the receiver spacecraft) is then 3 km away.

Assuming a spidernet wire mesh with $d = 5$ m wire spacing, frequencies up to $\sim 50$ MHz are reflected. If the spidernet radius is $R = 500$ m, the area is $A = 8 \times 10^5$ m$^2$ and the total length of wire required to weave the net is $L = 2A/d = 300$ km. If the wire mass per length is the same as given above (0.34 kg/km), the total wire mass is then 100 kg. An equivalent solid membrane dish of the same area would be much heavier, or about 2000 kg if one uses a very thin membrane of 1 $\mu$m thick and with aluminium mass density. The mass estimate of 100 kg was based on wire diameter 0.4 mm. Probably most of the wires could be thinner because they are repeated every 5 m; a few tens of kilograms might be a realistic estimate for the spidernet mass. On the other hand, to keep the spidernet in its shape it needs to be rotated and a mass which is a few times larger than the spidernet mass must reside on the circumference. The actual mass of the reflector construction depends on the adopted spin rate, the wanted upper frequency limit and the employed materials, but the above consideration shows that reaching a mass of as small as 100 kg is not out of the question.

The shape of the parabolic spidernet reflector needs not be very accurate at the long wavelengths and long focal length considered here. A numerical experimentation using the NEC code shows that even a cone-shaped reflector works almost as well as a parabola for the parametre values discussed above. As is well-known for parabolic dishes, the directivity of the antenna as a whole is low for low frequencies and increases up to the cutoff frequency which is determined by the mesh spacing of the spidernet. For example, with dish radius of 500 m, a directivity of 16 dB is obtained at 4 MHz.

The deployment of a spidernet with its support wires (Fig. 2) should occur automatically by the centrifugal force. The technical construction of the reflector spacecraft is made easier by the fact that it does not need many other devices or outstanding instruments.

## 3.3. Receiver cooling

Based on currently existing measurements of the galactic radio noise at low frequencies, cooling of the receiver should be unnecessary since the sky temperature is much larger than 300 K. However, since accurate maps of the radio sky at low frequencies have not been made, including a simple passive radiator cooling down to $\sim 30$ K might still prove valuable since the background emission may turn out to consist of pointlike sources in some regions of the sky.

## 3.4. Orbit selection and baseline for interferometry

To avoid manmade signals, a radioastronomical spacecraft should be either orbiting the Moon so that it is periodically behind it or it should be as far away from the Earth as possible, possibly even orbiting the Sun. In the Moon orbit case, data must be stored in the spacecraft and transmitted to Earth when the eclipse period stops, or it must be relayed to Earth by yet another spacecraft. Nowadays it is no problem to have sufficient memory onboard to store eclipse period data, so the Moon orbit is attractive because of its other benefits, e.g. cheaper communication link to Earth because of the relatively short distance. However, if the wanted interferometer baseline is longer than the radius of the Moon, the Moon orbit cannot be used. The maximum feasible baseline is determined by the amount of scattering and bending caused by interstellar and interplanetary plasma. The properties of interstellar plasma (density and density gradients) are still largely based on models rather than data (Rickett 1990, Linfield 1996), so accurate answers do not exist. It has been estimated by the ALFA proposal scientists that baselines longer than 100 km are not useful in the 0.03-30 MHz range (Jones et al. 2000); however, this estimate is based on the assumed average properties of the interstellar plasma in the kiloparsec scale. It may be that especially in our local neighbourhood ($< 30$ parsec) there are at least some directions where the interstellar plasma is tenuous and smooth enough to allow for higher angular resolution than the 10 arcmin what is provided by a 100 km baseline at 1 MHz. Especially when trying to observe exoplanets, the local neighbourhood is important, and there an angular resolution as high as possible is required, so it is our suggestion that the baseline should preferably be 500–1000 km, giving angular resolution of 1-2 arcmin at 1 MHz. Since the plasma effects decrease as $1/f^2$ and the angular resolution as $1/f$, at high frequencies the bottleneck is the spacecraft separation rather than plasma effects.

## 4. Summary and conclusions

The purpose of this paper was to continue and refresh the interest towards low-frequency radio astronomy by pointing out one intriguing possible application area (exoplanets) and by outlining two possible technical constructions (one simple and one more ambitious) of a single-satellite

antenna with high directivity. Detecting nearby earthlike exoplanets with radio methods is certainly very difficult, but the same is true for any other method thus far proposed. Because the limits of the radio method depend strongly on the properties of the interstellar plasma, which are currently not accurately known, the way forward is to try and implement the method. In the best case one could study the same exoplanets by both optical, infrared and radio methods; while each method used alone is incomplete, they are much more powerful when used together.

Regarding the technical methods to construct spaceborne low-frequency antennas, the simpler solution, a logperiodic antenna in the spin plane is lightweight and relatively easy to construct. Its main drawback is a modest effective area and the fact that the instrument cannot be continuously pointed towards an object (this could also be a benefit if several objects are to be scanned during the spin).

The more ambitious solution, but still quite affordable and feasible using current technology, is a large spidernet parabolic network paired with a separate receiver satellite containing e.g. dipole antennas. To reflect low-frequency waves, a coarse mesh of thin conducting wires is enough, which makes it possible to construct very large dish reflectors with radius 500-1000 m with a mass as small as 100 kg.

Since the purpose of the paper is not to present a concrete new mission, there are many technical details that we did not investigate, for example, the optimal antenna configuration (set of dipoles, or perhaps spiral antennas) in the receiver satellite of the spidernet configuration. By bringing in the exoplanet viewpoint we wanted to exemplify that low-frequency arrays in space would be interesting also for magnetospheric and auroral physicists outside the traditional domain of radioastronomy. Interpreting an exoplanet radio data in an optimal way requires a detailed knowledge of magnetospheric physics and the ability to quantitatively simulate magnetospheric and auroral processes in conditions that are not exactly similar to any of the examples we have studied in the solar system.

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